VARIATIONS IN SOIL CHARACTERISTICS IN HIGH-ELEVATION GRASSLANDS AND ADJACENT FORESTS IN ARIZONA

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16-429-CA

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December 1, 1975

ABSTRACT

Extensive high-elevation grassland areas occur in the Apache National Forest of Arizona. Analyses of the chemical and physical properties of the grassland soils and adjacent forest soils were conducted to determine if sufficient variations existed which would retard or prevent the encroachment of trees from forested areas into grassland areas. Statistically significant variations were shown to exist between the soils of the two vegetation types. Though significant differences did occur, it is doubtful that they are sufficient to affect the growth of vegetation. The concentration of the major nutrient-elements was found to be within the range normally expected for subhumid to humid region soils. The absence of mycorrhizal fungi in grassland soils was confirmed by soil cultures and ocular examination. It is suggested that variations in landform and vegetation are responsible for differences in the chemical and physical properties of these soils and that differences are not the result of variation in the chemical content of the basaltic parent material.

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INTRODUCTION

The high-elevation grasslands and adjacent forests investigated in this study are located in the Apache National Forest, Apache County, Arizona. The study area itself comprises approximately 8-1/2 square miles of the northern part of the Black River Watershed.

Soils of the study area are underlain by 4,000 feet of Quaternary basalt (Wilson, 1962). Volcanic cinders cover much of the area and cinder cones are prominent in the northern portion of the study area. The landscape is a gently sloping and undulating high-elevation plateau, dissected by numerous small drainages. Elevations in the study area range from approximately 9,100 feet in the southern part to 9,764 feet (Wahl Knoll) in the north.

Mountain muhly, pine dropseed, and Arizona fescue are the dominant grasses. Forest vegetation is comprised of mixed conifers.

Seven grassland sites, six forest sites, and five grassland-forest boundary sites (Figure 1) were randomly chosen in areas considered representative of the characteristic vegetation types.

The object of the investigation was to provide data which would allow a comprehensive characterization of the high-elevation grasslands and adjacent forest soils and to determine if sufficient variation existed

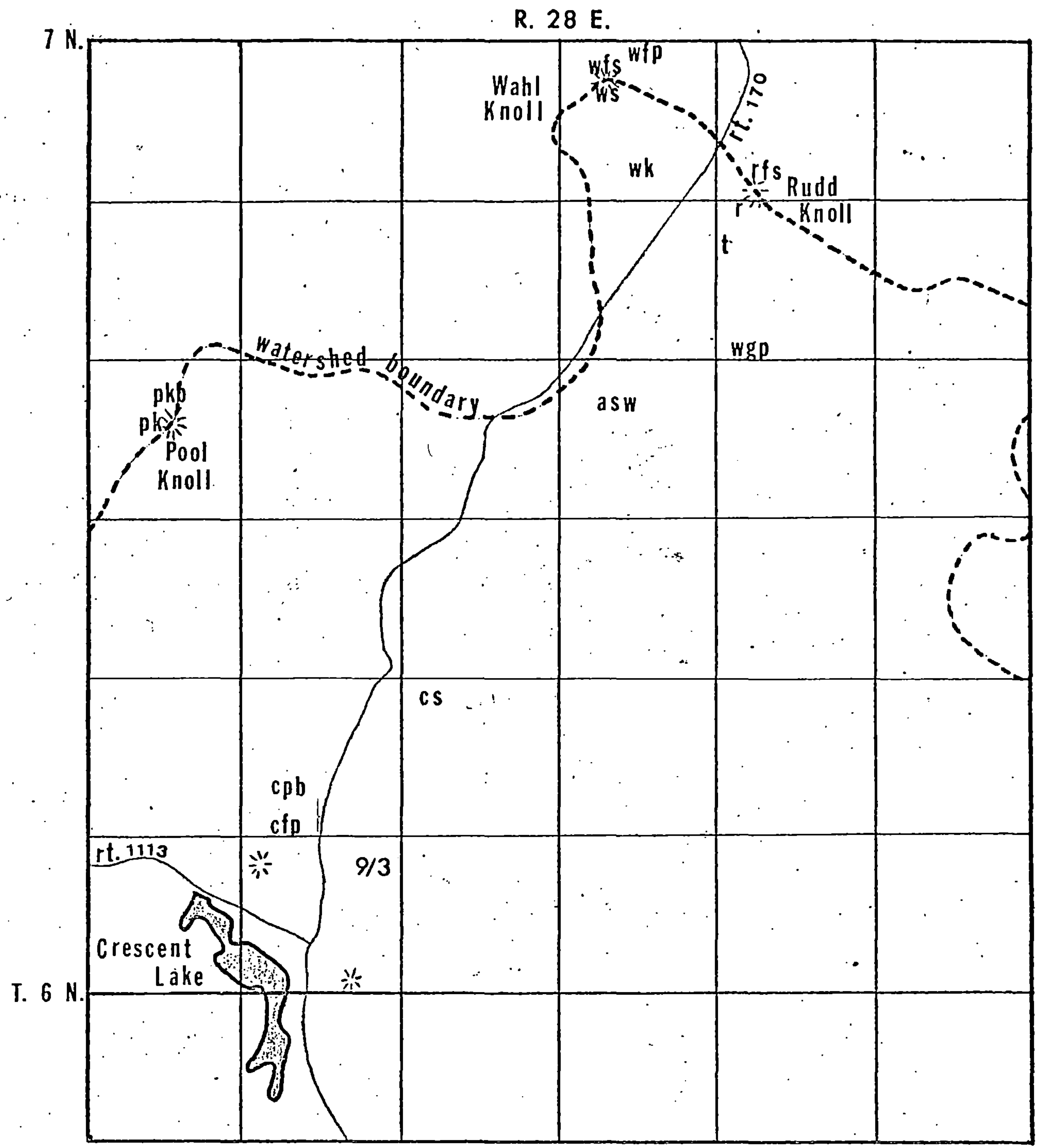

Figure 1. Location map of study sites

between them which would prevent or retard tree encroachment into grass-land areas from the adjacent forests.

CHARACTERISTICS OF GRASSLAND SOILS

Profile Characteristics

Seven grassland sites were selected for analysis representing the three soil series comprising the major portion of the study area. Each site was located in an area considered to be representative of the topography and vegetative cover of the respective soil series.

BANDERA SERIES (Bandera loam: sites R and T)

The Bandera series soils are noncalcareous, shallow, weakly developed, brown to reddish-brown, gravelly residual soils developing on steep slopes of volcanic cinder cones. Soils of this series are classified as lithic cryoborolls. The mollic epipedon rests directly on the C horizon which shows considerable variation in thickness.

Soil profile (Bandera loam)

A_1 0 to 4 inches, brown loam (7.5YR 5/2); loose; moderate granular structure; slightly acid; no visible effervescence with dilute HCl; many roots; 3 to 4 inches thick; clear, smooth boundary.

A_{12} 4 to 12 inches, reddish-brown (5YR 5/3) gravelly clay loam; soft; moderate granular structure; slightly acid; no

visible effervescence with dilute HC1; many roots; clear smooth boundary; 8 to 9 inches thick.

C 12 to 30 inches, pinkish-gray (5YR 6/2) cinder gravel mixed with clay loam soil; hard; weak coarse subangular blocky structure; slightly acid; no visible effervescence with dilute HC1; very few roots; 2 to 18 inches thick; abrupt smooth boundary.

CINDER SERIES (Cinder silt loam: sites WK and WGP)

The Cinder series soils are noncalcareous, shallow to moderately deep, well-developed, dark brown to light brownish-gray, residual soils developing on gently sloping hillsides and plateaus. Soils of this series are classified as lithic cryoborolls.

Soil profile (Cinder silt loam)

A_1 0 to 6 inches, dark brown (7.5YR 3/2) silt loam; loose; fine and medium granular structure; slightly acid; no visible effervescence with dilute HC1; many roots; 4 to 6 inches thick; clear smooth boundary.

A_{12} 6 to 10 inches, dark brown (7.5YR 3/2) silt loam; measurably lower organic matter than A_1; loose; fine and medium granular structure; slightly acid; no visible effervescence with dilute HC1; many roots; 4 to 6 inches thick; clear smooth boundary.

B_2 10 to 24 inches, light brownish-gray (10YR 6/2) clay; sticky when wet; moderate subangular blocky structure; slightly acid; no visible effervescence with dilute HC1; many roots; 6 to 14 inches thick; clear smooth boundary.

C 24 to 32 inches, light brownish-gray (10YR 6/2) mixture of cinders and loam soil; hard; weak coarse subangular blocky structure; slightly acid; no visible effervescence with dilute HC1; very few roots; 3 to 8 inches thick; abrupt smooth boundary.

BIG LAKE SERIES (Big Lake gravelly loam, Big Lake stony loam: sites ASW, CS-1, and CS-2)

The Big Lake series soils are noncalcareous, shallow, gravelly to stony, loam to clay loam residual soils developing on plateaus and sideslopes along drainages. The surface layer is a gravelly, cobbley, or stony loam. The subsoil is a stony clay loam. The depth to consolidated basalt is 12 to 27 inches. These soils are classified as lithic cryoborolls.

Soil profile (Big Lake gravelly and stony loam)

A 0 to 12 inches, dark brown (7.5YR 3/2) gravelly, cobbley or stony loam; loose; medium granular structure; slightly acid; no visible effervescence with dilute HC1; many roots; 6 to 12 inches thick; smooth clear boundary.

B_2 12 to 27 inches, brown (7.5YR 5/4) stony clay loam; slightly hard; small cracks develop on drying; moderate subangular blocky structure; slightly acid; no visible effervescence with dilute HCl; many roots; 6 to 15 inches thick; abrupt smooth boundary.

Physical properties

Samples of the Bandera series soils were taken along two straight-line transects on the south slope of Rudd Knoll (9,578 El.). One profile pit was excavated at the greatest soil depth (30 in.) encountered along transect T. Transect T trended north-south, perpendicular to map contours, ending near the summit of Rudd Knoll. Transect R trended east-west, parallel to map contours, slightly down-slope from the ridge crest of Rudd Knoll. The sampling interval was 100 feet. Depth probes, consisting of driving a measured steel rod into the soil to complete resistance, were made at each sample site at radial distances from the site ranging from 20 to 100 feet.

Soil depths for the Bandera series soils ranged from 10 to 30 inches, with the average depth being approximately 19 inches. The shallowest soils generally occurred at higher elevations on the slope of Rudd Knoll. The deepest soils occurred near the middle of transect T in the trough of a small undulation which trended northwest-southeast. At this point, a pit was excavated to study soil profile characteristics of the Bandera

series soils. Depth probes at a distance of 100 feet (parallel to slope contours) from each T stop indicated only slight variation in soil depth. Greater variations were apparent perpendicular to slope contours. Transect R also showed only slight variations in depth parallel to slope contours.

A depth-analysis of the Bandera series transects indicates that little variation exists in soil depth parallel to slope contours on Rudd Knoll, while considerable variation is apparent in the direction perpendicular to slope contours. Soil development appears to have been more extensive in locally flattened areas or in troughs of small undulations on Rudd Knoll.

Bulk densities along transect T ranged from 1.39 to 1.84, with the average being 1.63. Generally higher bulk densities were prevalent along the down-slope half of transect T, and are attributable to the greater percentage of gravel-size cinder material distributed throughout the soil profile. The up-slope half of transect T showed an average C-horizon gravel (greater than 2 mm) content of 31 percent, while the down-slope half averaged 59 percent. It is possible that the greater percentage of lower-slope gravel-size cinder material is the result of gravitational movement of these particles down-slope during the original volcanic activity associated with the formation of Rudd Knoll, or by subsequent mass-movement processes.

Bandera series soils are well-drained. Leven and Stender (1967) reported infiltration and permeability rates of 2.5 to 5.0 inches per hour. Water readily penetrates the parent cinder material, but drainage through the underlying basalt bedrock is restricted to fractures.

Two sites (WGP and WK) were selected which were considered representative of the Cinder series soils. Site WGP was a pit excavated to depth of 24 inches. Site WK consisted of a straight-line transect trending northwest to southeast on the gentle slope south of Wahl Knoll. The sampling interval for transect WK was 100 feet. Four depth probes were made at radial distances of 50 feet from each sampling stop along the transect to determine local variation in soil depth.

Cinder series soils ranged in depth from 16 to 32 inches with an average depth of 21.5 inches. The shallowest soils generally occurred on the crests of small undulations, while the deepest soils tended to occur in the troughs of undulations. Observed transect soil depths and areal depth probes to welded cinders indicated that variation in the depth of Cinder series soils is very local, resulting from slight variations in topography. No apparent gradation in depth due to the influence of slope was indicated.

The bulk density of Cinder series soils varies considerably areally and with depth. Variations are apparently due to the distribution of gravel in the profile and possibly the effect of frost heaving. Bulk densities along transect WK were determined for clod samples taken from a

depth of six inches. Densities at this depth ranged from 1.39 to 1.82, with the average being 1.62. Soils with low bulk densities contained an average of 6 percent gravel and were very loose. Soils with higher bulk densities contained an average of 21 percent gravel and were not as loose as samples with low bulk densities. Soil samples along transect WK were taken during early Spring while there was still abundant snow cover in scattered areas. In all instances, samples having a bulk density less than 1.62 were taken from sites exhibiting evidence of frost heaving. Soil depth at these sites ranged from 16 to 18 inches and were the shallowest soils encountered along transect WK.

Site WGP consisted of a pit excavated to a depth of 24 inches, located on gently undulating terrain south of Rudd Knoll. Bulk densities at this site ranged from 1.40 (0-6 in.) to 1.74 at a depth of 24 inches. The surface horizon contained an average of 8 percent gravel with gradation to 42 percent gravel in the C horizon. Material from the B_2 horizon developed small cracks when allowed to become air-dry in the laboratory, indicating the presence of some swelling-type clays. When moistened, soil from the B_2 horizon became plastic and sticky, with cracks disappearing.

Big Lake series soils are generally the shallowest soils of the grasslands. They are moderately well-developed, lacking a C horizon. The A and B horizons contain considerable amounts of gravel and cobble throughout.

Site ASW was located on the steep sideslope of a drainage in gently undulating to flat terrain approximately one mile south of Wahl Knoll. Soil depth at this site was 18 inches. The surface horizon contained 13 percent gravel, of which approximately 80 percent was greater than 0.5 inch in diameter. The bulk density of the surface horizon was 1.24. It is speculated that the bulk density of the surface horizon may be higher than indicated. Obtaining clods of sufficient size to contain a representative proportion of gravel-size material were rendered difficult by the dry condition of the soil and the lack of cohesiveness. Representative clods were obtainable at depths of 12 and 18 inches and gave bulk densities of 1.83 and 1.88 respectively. The lower A horizon and the B horizon contained numerous gravel, stones, and cobble, undoubtedly accounting for the considerably higher bulk density.

Sites CS-1 and CS-2 were located on nearly level terrain approximately three miles south of Wahl Knoll. The soil depth at site CS-1 was was 12 inches, increasing to 27 inches at site CS-2. Basalt outcrops were common near these two sites and the surface was strewn with basalt fragments ranging in size from large gravel to small boulders. Fifty depth probes to consolidated basalt around the circumference of two circles 400 feet in diameter, with each site at the center, indicated that the depth to basalt ranged from 3 to 29 inches. Eighty-two percent (41) of all depth probes showed a depth to basalt ranging from 8 to 18 inches. Two probes

were greater than 18 inches in depth and seven probes were less than 8 inches in depth. Both probes with depths greater than 18 inches (26 and 29 inches) were located in the approximate centers of small "mima mounds" which are commonly associated with Big Lake series soils. Probes through the diameter of the mounds, which were approximately 10 feet in diameter, showed that a concave depression existed in the basalt bedrock beneath these mounds.

The nature and origin of these "mima mounds" has not been extensively studied nor was it within the objective of this research to study their characteristics. However, an hypothesis regarding the origin of these mounds is given.

True "mima mounds" are presumably associated with pocket gopher activity (Glossary of Geology, p. 454). Whether the mounds associated with Big Lake series soils are the result of animal activity is questionable. Animal burrows were more prevalent in these mounds than in the surrounding soil and could explain the existence of the mounds. However, it is unlikely that animal activity is responsible for the depressions in basalt bedrock.

More likely, the depressions are the result of increased chemical weathering along fractures in the basalt (Hunt, 1972). Drainage in Big Lake series soils is limited to lateral movement, or through fractures in basalt bedrock. Chemical weathering and soil development would likely be more extensive along these fractures, ultimately forming a shallow

depression filled with unconsolidated residual material. Subsequent animal activity and the establishment of vegetation could account for mound-building. Eolian-transported material trapped and accumulated by vegetation would enhance the mound-building process.

Bulk densities of Big Lake series soils ranged from 1.26 for the surface horizon to 1.74 at a depth of 18 to 27 inches. The proportion of larger rock fragments increases noticeably with depth and is especially evident in the deeper soils of the Big Lake series.

The average bulk density of the three grassland soil series investigated did not vary greatly. Cinder series soils showed the highest average bulk density of 1.64 while the Big Lake and Bandera series soils had average bulk densities of 1.58 and 1.57, respectively. Transect R showed the lowest average bulk density (1.36) and was the only site having an average bulk density significantly less than all other sites. Site CS-2 had an average bulk density (1.53) that was significantly less than site WGP only.

The bulk density of the soils investigated appears to be largely related to the gravel content of the soil. Soil samples taken along transect R were nearly gravel-free as were samples from CS-2. Most of the fragmental rock material contained in the CS-2 profile was as large or larger than the clods extracted for the determination of bulk density, thus having little effect on the density of laboratory samples and accounting for the significantly lower bulk density.

In general, deeper soils exhibited higher average bulk densities attributable to the influence of increasing gravel content and compaction with depth. The thickness of the C horizon or the absence of the C horizon also appears to have an influence on bulk density. Soils with thin C horizons or that lack the C horizon exhibit lower bulk densities than soils having thick C horizons.

Chemical properties

Soils of the Bandera, Cinder, and Big Lake series are residual soils developing from basaltic parent materials. The essential minerals of basalt are pyroxene and a calcic or intermediate plagioclase feldspar (Spock, 1962). The composition of pyroxene can be represented by the generalized formula $R^{++}SiO_3$, wherein the bivalent R almost invariably includes magnesium. Magnesium commonly occurs alone but it also may occur with ferrous iron, calcium, or both. The plagioclase minerals commonly found with pyroxene in basalt range from labradorite ($Ab_{50}An_{50}$-$Ab_{30}An_{70}$, where Ab and An refer to the relative proportions of sodium feldspar and calcium feldspar, respectively) to anorthite ($Ab_{10}An_{90}$) (Dana, 1959).

The three grassland soil series investigated are distinctly non-calcareous, showing no visible effervescence with the application of dilute HCl. Atomic absorption analyses revealed an average calcium content of 2424 ppm (parts per million). Cinder series soils contained an

average of 2506 ppm calcium as compared to 2083 ppm and 1627 ppm for the Big Lake and Bandera series soils, respectively.

The low calcium content of these soils, developed from usually calcium-laden parent materials combined with the hydrological properties of the cinder parent materials and underlying basalt bedrock, suggest that much calcium has been removed from the soil profile by leaching. As calcium ions are released into the soil solution by chemical weathering processes, they may be reprecipitated as some form of calcium carbonate, absorbed on the cation-exchange complex, or may move downward with percolating water. The absence of horizons with significantly higher accumulations of calcium provides additional evidence that calcium losses occur by drainage.

The drainage characteristics of the three grassland soil series do not vary greatly nor does the apparent composition of the parent materials. Two sampling sites, ASW and R, exhibited an average calcium content significantly less than other sites. Both of these sites were located on steep slopes, ASW on the steep sideslope of a drainage and R on the steep slope of Rudd Knoll. The chemical composition of basalt, on a local basis, is generally so uniformly homogeneous that variations in calcium content, as a result of variations in basalt composition, can probably be disregarded. When compositional and topographical factors of all sites are considered, it appears that slope steepness affects drainage characteristics which, in turn,

influence calcium losses by leaching. Soils having a higher calcium content were invariably located on nearly level, gently undulating, or gently sloping terrain.

Site CS-2 (Big Lake series) exhibited the highest calcium content of all grassland sites with an average of 2576 ppm. Soil depth at this site was 27 inches, with the B horizon resting directly on unweathered basalt bedrock. The adjacent site, CS-1, contained 2471 ppm calcium and was statistically equivalent to CS-2. Although calcium losses by leaching at these two sites are probably less than losses in Bandera series soils, at least part of the total calcium determined in the laboratory is assumed to be additionally derived from the acid digestion of relatively unweathered fine basalt fragments contained in the soil sample. A similar situation exists for Cinder series soils in which a portion of the total calcium determined by laboratory analysis is derived from relatively unweathered cinder material from the C horizon.

A regression analysis (Figure 2) for calcium distribution in grassland soil profiles indicates that calcium increases by approximately 19 ppm with each 1-inch increase in soil depth. That calcium content increases with depth suggests that a calcic horizon may be slowly developing as calcium is precipitated from the soil solution. More likely, apparent increases in calcium are a reflection of the residual calcium content of basalt and cinder material determined in laboratory analyses. Under the

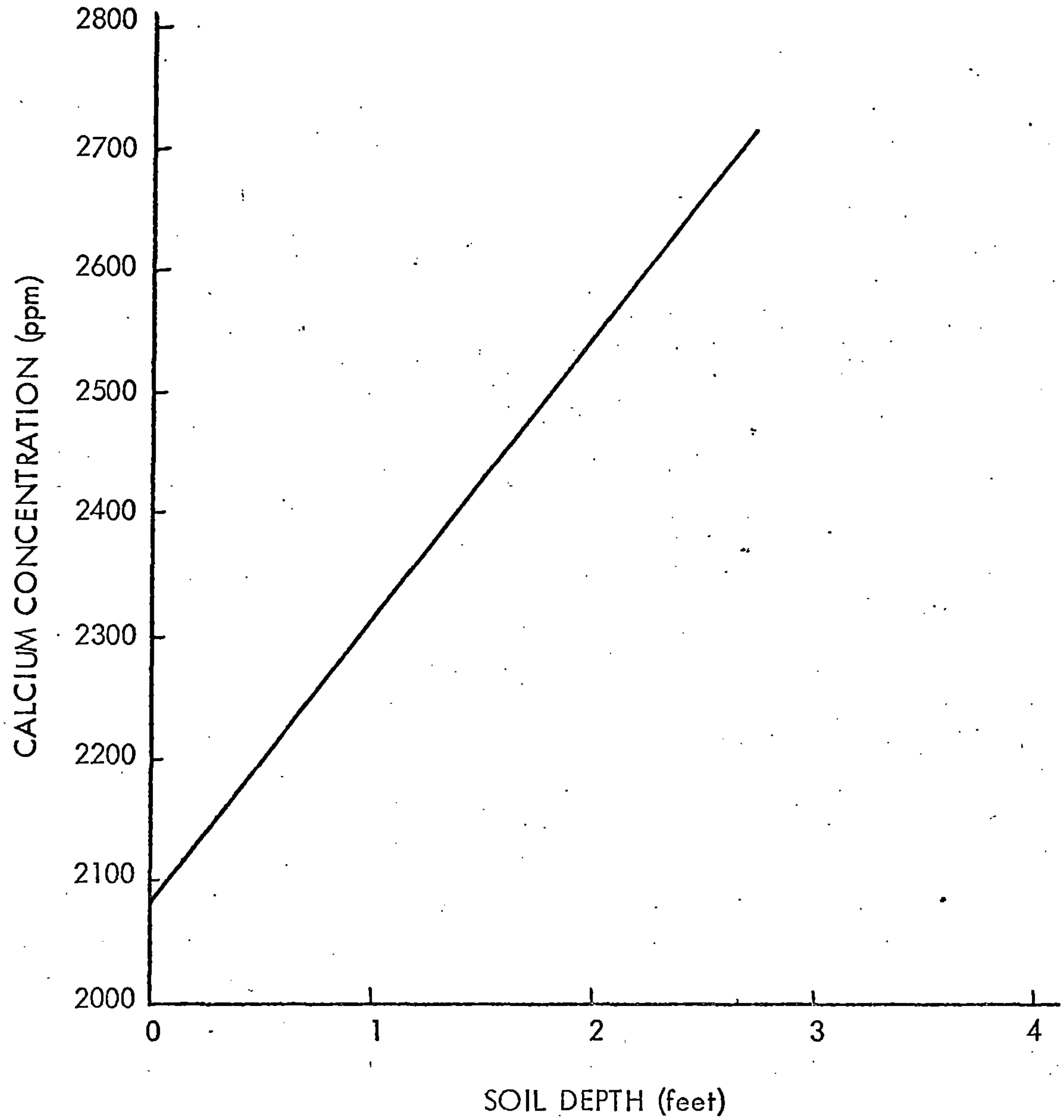

Figure 2. Regression Estimate of Calcium Distribution with Depth in Grassland Soils

slightly acid pH conditions which prevail in grassland soils, much of the cation-exchange complex is undoubtedly occupied by hydrogen ions. Big Lake and Cinder series soils both have B horizon textures dominated by clays and it is reasonable to assume that the increase in calcium abundance with depth is also partially influenced by the amount of calcium adsorbed on clay particles and other colloidal matter.

Magnesium appears to be uniformly distributed in grassland soils. No statistically significant variations in magnesium content were observed among grassland sites.

The magnesium distribution in grassland soils bears similar resemblance to calcium distribution as could be expected from its inclusion in the composition of the essential minerals of basalt and its similarity with the chemical properties of calcium. To the extent that very slight variations in magnesium concentration occurred, Cinder series soils contained an average of 894 ppm while Big Lake and Bandera series soils contained 878 ppm and 819 ppm, respectively.

A slight increase in magnesium content with depth was indicated by a regression analysis (Figure 3). For each 1-inch increase in depth, magnesium increased by approximately 6 ppm.

The potassium content of grassland soils is within the range normally expected for humid to subhumid region mineral soils (Buckman and Brady, 1969). Grassland soils contained an average of 7857 ppm total potassium, most of

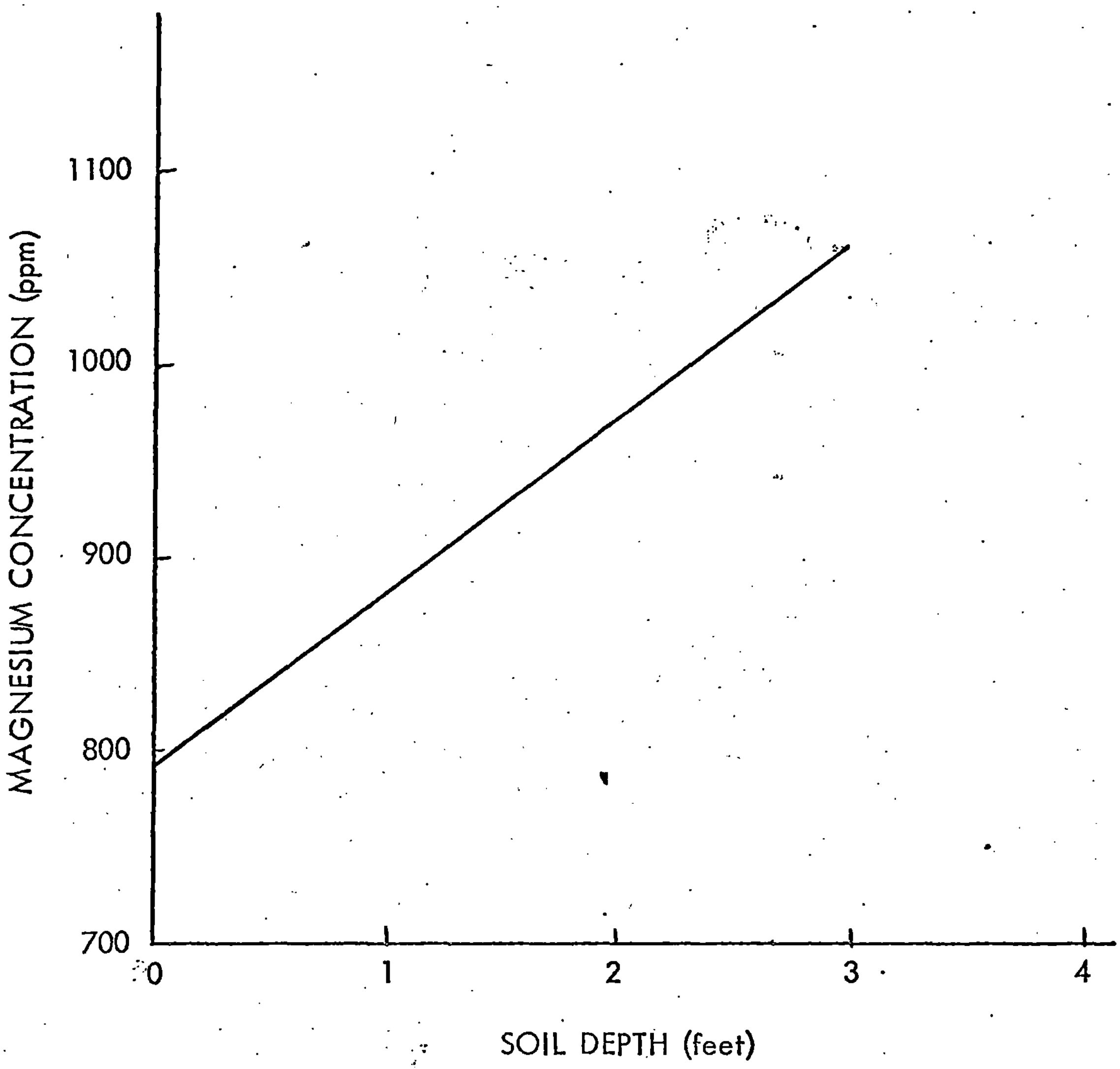

Figure 3. Regression Estimate of Magnesium Distribution with Depth in Grassland Soils

which must be considered unavailable to plants. The readily available potassium constitutes only 1 or 2 percent of the total potassium and exists in the soil in two forms, potassium contained in the soil solution and exchangeable potassium adsorbed on the surface of colloidal particles.

Potassium, as potash feldspar, is commonly present in igneous rocks. Its abundance may be appreciable if sodic plagioclase is a major mineral constituent but if calcic plagioclase is dominant, its amount is low (Spock, 1962). The feldspars are fairly resistant to weathering, calcic plagioclase being the more susceptible. Because of the stability of the feldspars, potassium is slowly released by weathering processes and, while the most significant losses probably result from leaching, the losses are generally not important.

The most significant variation in potassium content of grassland soils occurred at site ASW located on the steep sideslopes of a drainage. In this instance, the lower content could possibly have resulted, at least partially, from leaching. While significant variation is indicated at this site, potassium content remains within an acceptable range, varying only 500 ppm from the grassland average of 7857 ppm.

Big Lake series soils contained the highest average amount of potassium with 8018 ppm, followed by the Bandera series with 7880 ppm, and the Cinder series with 7732 ppm. In general, soils lacking the C horizon or with only a thin C horizon contained the greatest amounts of

potassium, suggesting that potassium content is related to the resistance of the original minerals to weathering. More extensive weathering would tend to release potassium which would be removed by drainage water; less weathered minerals would contain more of the original potassium.

Regression analysis indicated that potassium increases with depth in grassland soils (Figure 4). Each 1-inch increase in depth results in an increase of approximately 24 ppm potassium.

Significant variation in sodium content occurs among almost 48 percent of grassland sites. Big Lake and Cinder series soils contained the highest average amounts of sodium with 269 ppm and 260 ppm, respectively. Bandera series soils contained an average of 230 ppm sodium.

The distribution of sodium among grassland sites approximates the distribution of calcium and magnesium, suggesting that much of the sodium remains chemically combined in the original feldspar minerals. If calcium and magnesium are the dominant metallic cations adsorbed on colloidal particles, sodium would tend to be removed from the soil profile by leaching. Variations in sodium content among grassland sites do not appear to be important, first because sodium is not an essential element in plant nutrition, and secondly, soils of the grasslands exhibit good structure and the amounts of sodium present are apparently not sufficient to cause deflocculation.

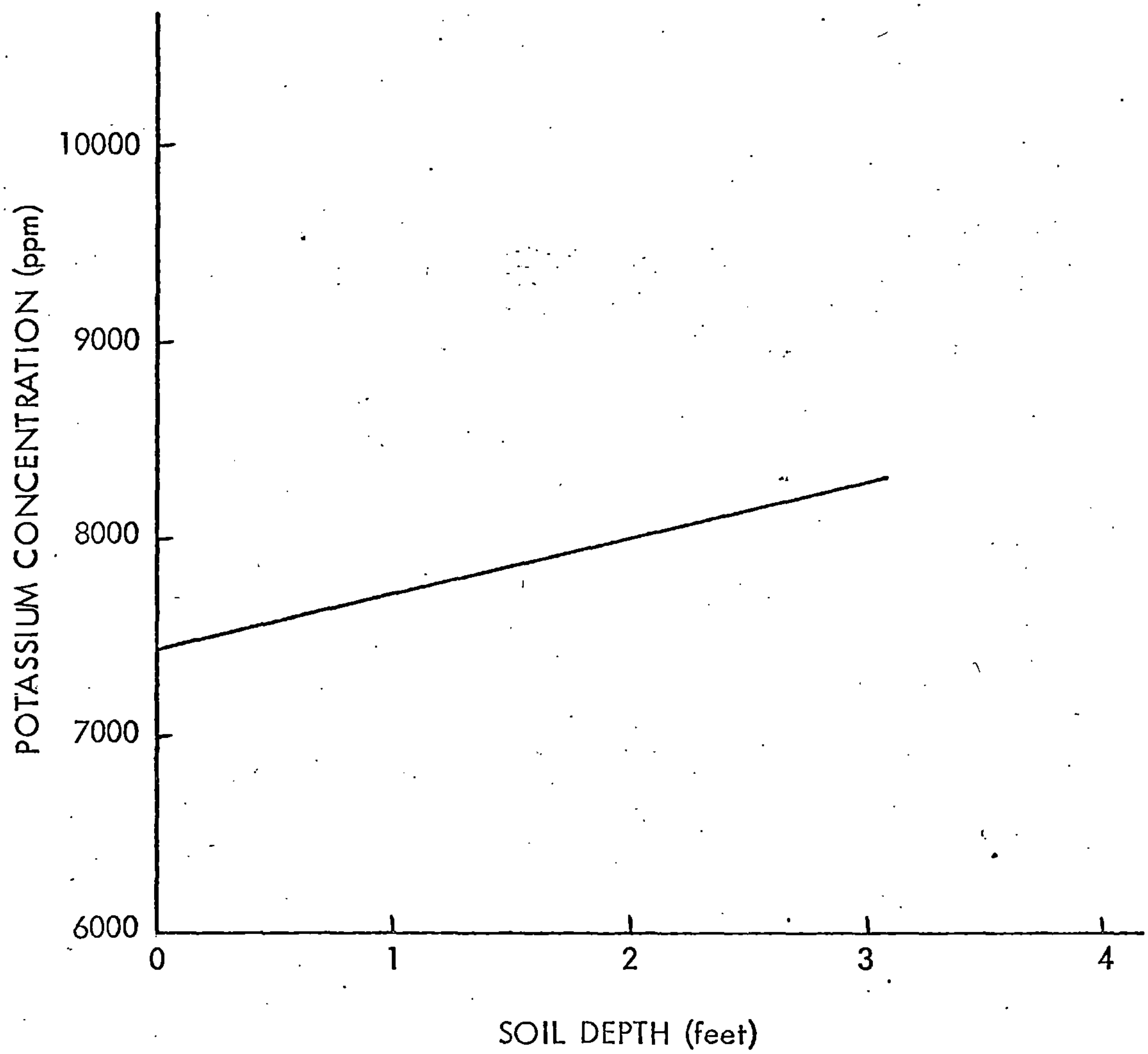

Figure 4. Regression Estimate of Potassium Distribution with Depth in Grassland Soils

Regression analysis indicates that sodium is evenly distributed throughout the soil profile, increasing by slightly more than 2 ppm with each 1-inch increase in depth (Figure 5).

Only slight variation in phosphorus content exists in grassland soils. The only sites that did vary significantly were CS-1 and CS-2.

The range of phosphorus that ordinarily may be expected in mineral soils of humid to subhumid regions varies between 100 ppm and 2,000 ppm. The phosphorus content of grassland soils is slightly above the lower limit of this range, averaging approximately 206 ppm. This low phosphorus content is possibly a reflection of the inherently low amount of phosphorus (average 290 ppm) usually present in basalt. Because of its comparatively high insolubility, very little phosphorus is likely to be lost by leaching, resulting in the concentration of phosphorus by organic matter in the surface layers of the soil.

Regression analyses indicated that there is a very slight increase in phosphorus concentration with depth in grassland soils (Figure 6) while forest and forest-grassland interface areas show a slight decrease in phosphorus concentration with depth. The phosphorus content of grassland soils is possibly influenced by the summer grazing of livestock and wildlife. Phosphorus is normally concentrated near the soil surface by the decomposition of plant residues. Below-ground decomposition of plant roots redistributes phosphorus throughout the soil profile, especially in shallow

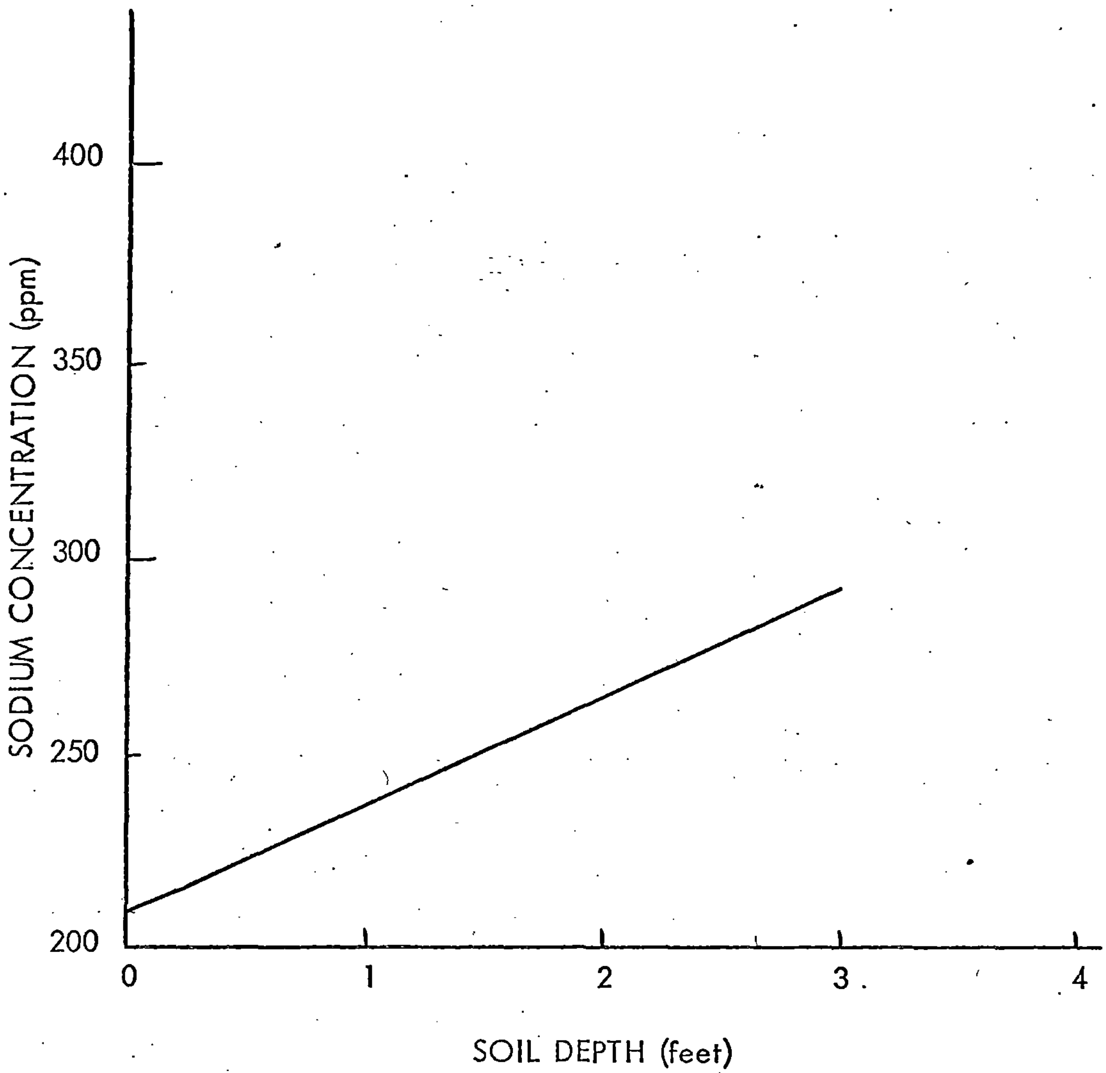

Figure 5. Regression Estimate of Sodium Distribution with Depth in Grassland Soils

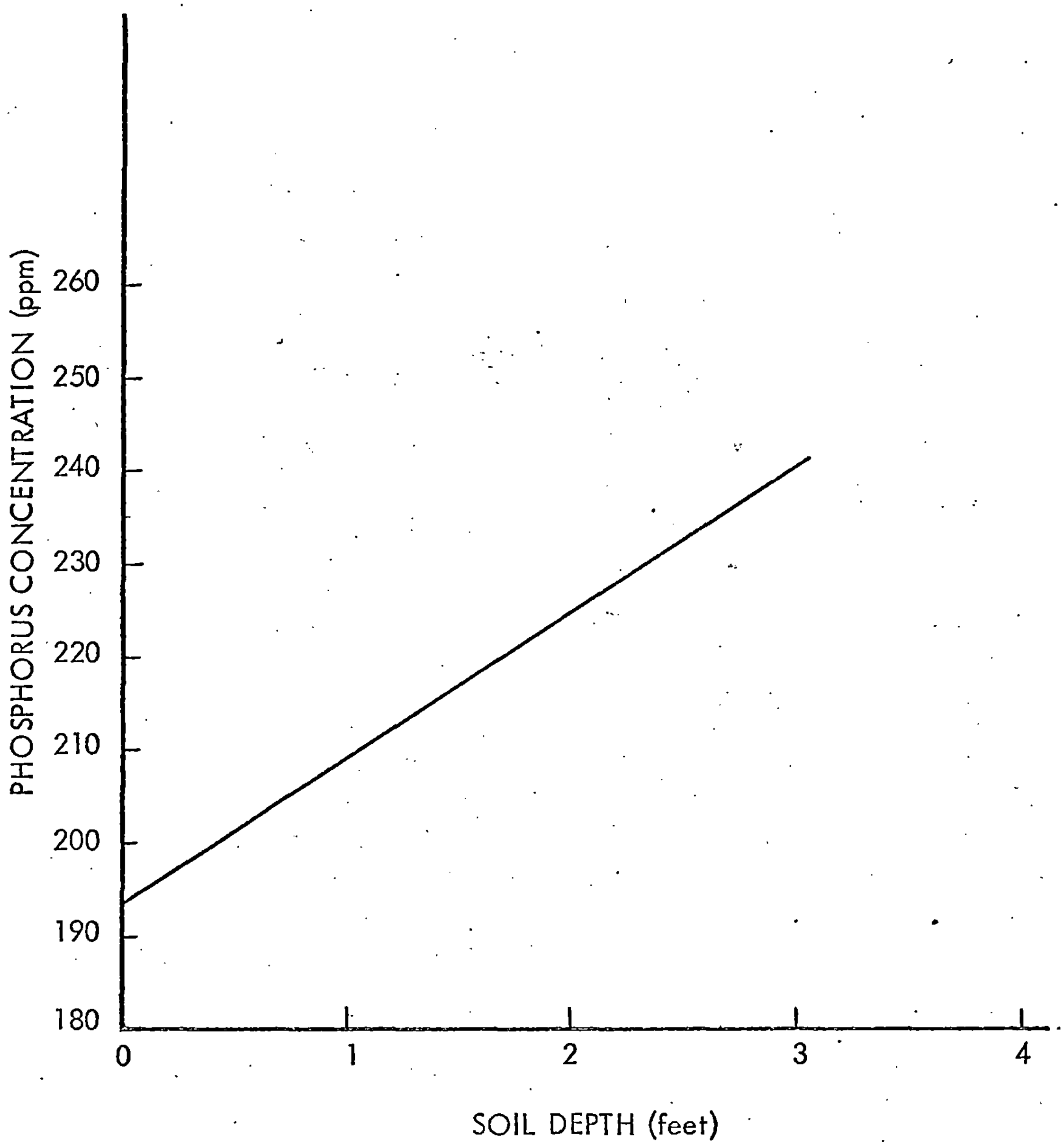

Figure 6. Regression Estimate of Phosphorus Distribution with Depth in Grassland Soils

soils. The continuous removal of the above-ground plant material, such as by grazing, would tend to slow the rate at which phosphorus accumulates near the surface from the decomposition of residues and could account for the slight increase in phosphorus concentration with depth in grassland soils.

Nitrogen concentration is highest in the Bandera series soils (0.253%) as compared to 0.183 percent for Big Lake soils and 0.119 percent for Cinder series soils. Since the density of grass cover is essentially the same at all grassland sites, the average nitrogen content is possibly related to the amount of organic matter incorporated into the soil in relation to soil volume.

Bandera soils lack the B horizon and root penetration into partially weathered cinders is restricted. Under this condition, root exploitation of the A horizon is encouraged (Volobuev, 1964) and the amount of organic residue incorporated into the soil on a soil-volume basis is greater than for the Big Lake and Cinder series soils. Big Lake and Cinder series sites were slightly deeper than Bandera sites, with average depths of 19 inches and 21.5 inches, respectively. Both of these soil series have B horizons that are easily exploited by roots, but the amount of organic residue incorporated into the soil, based on the soil volume, is less. Since organic matter and nitrogen both decrease with depth, the average concentration of these two constituents is apparently strongly influenced by soil depth.

Grassland soils are developing under cold, subhumid to humid climatic conditions. As a result, slightly acid pH values prevail as the metallic cations are leached from the soil by percolating water and are replaced by hydrogen at the cation-exchange sites. Soil pH values in the grasslands, as determined by pH meter in a 1:1 soil paste, range from 6.1 in the Bandera soils to 6.5 in the Big Lake soils. In general, pH values tended to be lower in soils developing on steep slopes where leaching of the metallic cations appears to have been most extensive.

In the section entitled Statistical Analyses, Table 1 summarizes the mean nutrient and pH data for grassland soil samples. These data were used for analysis of variance calculations, regressions, and statistical comparisons between treatment means.

CHARACTERISTICS OF FOREST SOILS

Profile characteristics

Six forest sites were selected for analysis, representing the Sponseller series of soils. Sponseller soils are the major timber-producing soils adjacent to the grasslands, occupying moderately steep to steep slopes of volcanic cinder cones or cinder-cone remnants. Sampling sites ranged in elevation from approximately 9,100 feet to 9,600 feet. The vegetation type is predominantly mixed conifer.

Sponseller soils are noncalcareous, deep, moderately well-developed, gravelly or cobbley, residual soils developing on the slopes of volcanic cinder cones.

Soil profile (Sponseller loam)

O 0 to 3 inches, fresh and partially decomposed mixed-conifer litter; 2 to 3 inches thick.

A 0 to 12 inches, dark brown to dark reddish-brown (5YR 3/2) gravelly loam; fine to medium granular structure; moderately acid; no visible effervescence with dilute HCl; many lateral tree roots; 10 to 12 inches thick; clear smooth boundary.

B 12 to 48+ inches, reddish brown (5YR 5/3) clay or clay loam; subangular blocky structure; moderately acid; no visible effervescence with dilute HC1; widely spaced tree roots below 20 inches; 14 to 36+ inches thick; abrupt smooth boundary.

Physical properties

Six pits ranging in depth from 26 to 48 inches were excavated for the study of the Sponseller series forest soils. The pits were located on slopes varying from gentle to steep, with a vegetation cover of predominantly mixed conifer. Very sparse grasses occured on the gentle slopes under areas with less-dense forest canopy. The slopes on which the pits were located had topographical aspects of north, northeast, and west.

Site WFS was located on the steep north slope of Wahl Knoll at approximately 9,500 feet elevation. The surface was covered with approximately 30 percent cobble with smaller rock fragments comprising less than 5 percent. Localized accumulations of large rock fragments occur commonly throughout the steep north slope.

The O horizon had a maximum thickness of two inches and was composed primarily of pine litter in various stages of decomposition. The A horizon, 0-10 inches, was a dark brown, gravelly loam with fine to medium granular structure. The average A horizon gravel content was 15 percent. The average clay and silt fractions were 26 and 36 percent,

respectively. Many small lateral roots of nearby pine trees were evident in the A horizon. The B horizon, 10-45 inches, was a dark reddish-brown gravelly clay exhibiting subangular blocky structure. The average textural composition was 43 percent clay and 31 percent silt. An average of 21 percent gravel was contained throughout the B horizon. Tree roots were plentiful in the uppermost part of the B horizon, decreasing both in size and number with depth. The average bulk density of the A horizon (1.48) and the B horizon (1.66) appeared to be largely related to root abundance and gravel content.

Depth probes to consolidated material were conducted parallel and perpendicular to slope contours. Probes spaced at 50-foot intervals along the 9,500-foot contour indicated little variation in depth. Probes spaced at 50-foot intervals up-slope and down-slope from the sampling site indicated that soil depth decreased up-slope to a minimum depth of 6 inches at the forest-grassland boundary. Soil depth down-slope from the sampling site showed no substantial variation.

Site WFP was located on the moderately steep north slope of Wahl Knoll at an elevation of approximately 9,200 feet. Surface rock fragments consisted of approximately 22 percent gravel and 8 percent cobble. The distribution and percentage of the various rock fragments varied somewhat in the area of site WFP, with higher proportions of cobble apparently associated with small basalt outcrops or shallow soil. Aspen trees appeared

to be predominant in localized areas exhibiting high proportions of cobble, with lesser amounts of smaller rock fragments.

The depth of soils developing on the lower slope of Wahl Knoll varied considerably, ranging from 51 inches to 10 inches. Deeper soils invariably occurred in areas with a low proportion of surface cobble, whereas shallow soils generally occurred in areas in which cobble was the prevailing surface rock fragment. Variations in soil depth occurred in all directions from the sampling site but were generally greater and more numerous in directions parallel to slope contour and down-slope from the sampling site.

Organic litter was almost absent in areas with a high proportion of surface cobble while gravelly sites exhibited an organic horizon two to three inches in thickness. The O horizon at site WFP was two inches in thickness and composed of mixed conifer litter in various stages of decomposition. The A horizon, 0-12 inches, was a dark brown loam with fine to medium granular structure, containing approximately 9 percent gravel. Textural analyses showed an average A-horizon composition of 23 percent clay and 41 percent silt. Small lateral tree roots were very numerous, forming a loosely matted network throughout the A horizon. Several root channels containing decayed root material or other organic debris occurred less frequently in the upper eight inches of the A horizon. The B horizon was a reddish brown clay having an average textural composition of 46

percent clay and 35 percent silt. Gravel content was 13 percent. The B horizon exhibited moderately developed subangular blocky structure. Small roots were plentiful in the upper 12 inches of the B horizon, with a very few decaying roots present also.

The bulk density of the A horizon (1.27) and the upper 12 inches of the B horizon (1.22) was strongly influenced by root structure and abundance and by the rather high amount of organic matter.

Site 9/3 was located on the gentle west slope of a forested area about one mile northeast of Crescent Lake at an approximate elevation of 9,100 feet. Surface rock fragments were composed of approximately 22 percent gravel and 5 percent cobble. Variation in the distribution and relative abundance of gravel and cobble was similar to that of site WFP. Soils with a high proportion of surface cobble tended to be shallow, lacking a significant accumulation of surface organic debris. Deeper soils generally occurred in areas that were cobble-free or that had a low proportion of surface cobble. Gravelly sites characteristically exhibited organic horizons approximately two inches in thickness and composed of mixed conifer litter.

The depth of the soil at this site was 27 inches but depth probes in the area indicated variation from 13 to 33 inches. As was observed at site WFP, shallow soils generally occurred in cobble-strewn areas near basalt outcrops. There was no evidence that soils became shallower

up-slope from the sampling site. Depth probes in the adjacent grassland, approximately 200 yards from the sampling site, indicated that the forest soils at site 9/3 were generally deeper than the grassland soils.

The A horizon at site 9/3 was a dark brown loam with medium granular structure. The average textural composition of the A horizon (0-6 inches) was 25 percent clay and 36 percent silt. Ten percent gravel was contained in the A horizon. Many small lateral roots formed a moderately dense, somewhat matted, network throughout the A horizon. Old root channels filled with organic debris or decomposed roots occurred frequently. The B horizon (6-27 inches) was a reddish brown clay containing approximately 12 percent gravel. Textural analyses showed an average of 42 percent clay and 33 percent silt. The upper B horizon exhibited moderate subangular blocky structure, becoming more weakly developed below 18 inches. Roots were plentiful throughout the B horizon and a few old clay-skinned root channels were observed. Roots penetrating to the lower B horizon boundary exhibited lateral growth habit along the surface of consolidated bedrock.

The A horizon bulk density of 1.34 appeared to be strongly influenced by the abundance and structure of the root network, in combination with the relatively high proportion of organic matter. The B horizon had an average bulk density of 1.74.

Site PK was located on the moderately steep west slope of Pool Knoll at approximately 9,250 feet elevation. The surface cover of rock fragments was similar to that of sites WFP and 9/3, with 18 percent gravel and 11 percent cobble. Soil depth at this site was 31 inches. Depth probes indicated little variation in soil depth near the sampling site. Unlike sites WFP and 9/3, the relative proportion of surface rock fragments did not appear to be related to soil depth and no outcrops of consolidated rock material were observed within a 200-foot radius of the sampling site.

The O horizon at site PK was approximately two inches in thickness and composed predominantly of pine litter. The A horizon (0-10 inches) was a dark brown loam containing 8 percent gravel. Textural analyses showed an average content of 18 percent clay and 39 percent silt. Many roots, forming a loosely matted network, occurred throughout the A horizon. Many old root channels were observed and appeared to be more numerous than at sites WFP and 9/3. The B horizon was a reddish brown gravelly clay with a textural composition of 43 percent clay and 37 percent silt. Gravel content was 13 percent. Moderate subangular blocky structure was exhibited throughout the B horizon. Roots were plentiful and old root channels were especially numerous in the upper six inches of the B horizon. Clay skins occurred in larger root channels.

The average bulk density of the A horizon was 1.31, increasing to 1.66 for the B horizon. The bulk density of the A horizon and the upper

B horizon appeared to be strongly influenced by the abundance of roots and old root channels.

Site CFP was located on the gentle northeast slope of a small forested knoll about 1-1/2 miles north of Crescent Lake at an elevation of approximately 9,100 feet. The abundance of surface rock fragments at and near the sampling site was discernibly less than at the other sampling sites. Surface gravel at site CFP comprised approximately 8 percent. A few outcrops of rock occurred near the forest-grassland boundary, approximately 100 yards from the sampling site. Very few cobbles were associated with the outcrops and were generally absent throughout the sampling area. Soil depth at site CFP was 48 inches, with depth probes up to 100 yards distant from the sampling site indicating only slight variation in soil depth. Depth probes in the adjacent grassland north of the sampling site indicated that forest soils were more than twice as deep as the grassland soils.

The organic horizon was 1-2 inches in thickness and composed of mixed conifer litter. The A horizon (0-12 inches) was a dark brown gravelly loam. Gravel content was 13 percent. The average textural composition of the A horizon was 19 percent clay and 38 percent silt. Roots were plentiful throughout the A horizon but the loosely matted network of roots was distinctly less dense than at all other sampling sites. Old root channels were nearly absent. The B horizon (12-48 inches) was a very gravelly reddish brown clay loam. Gravel content was 23 percent. Roots were sparsely distributed throughout the B horizon and the old root channels were not evident.

Site CFP showed the highest average bulk density (1.77) of all forest sites. The A horizon exhibited an average bulk density of 1.63, increasing to 1.82 for the B horizon. The high bulk density at this site appeared to be the result of a fairly high gravel content and the lack of an extensive root network in combination with the low organic matter content, especially in the B horizon.

Site RFS was located on the steep north slope of Rudd Knoll at an elevation of approximately 9,300 feet. The surface at this site was covered with approximately 26 percent cobble. The abundance of cobbles varied throughout the study area near site RFS and was persistently high compared to the abundance of gravel. Surface gravel generally comprised less than 5 percent. Rock outcrops occurred commonly on the slope with increasing frequency toward the summit of the knoll.

Soil depth at site RFS was 26 inches. Depth probes up-slope from the sampling site indicated that soil depth decreased to a minimum of four inches at the forest-grassland boundary at the approximate ridge crest of Rudd Knoll. Down-slope from the sampling site, soil depth increased slightly to a maximum depth of 32 inches. Depth probes parallel to slope contour indicated no substantial variation in soil depth.

The O horizon at site RFS was one inch in thickness and composed primarily of pine litter. The A horizon (0-10 inches) was a dark brown gravelly loam with medium granular structure. Gravel content of the

A horizon was 12 percent. The average textural composition of the A horizon was 22 percent clay and 42 percent silt. The B horizon (10-26 inches) was a dark reddish brown gravelly clay with moderate subangular blocky structure. The gravel content of the B horizon was 17 percent. The average textural composition of the B horizon was 48 percent clay and 31 percent silt.

Small lateral tree roots were plentiful in the A horizon, forming a very loose network throughout. Old root channels were not evident. The B horizon contained a few small roots that exhibited a lateral growth habit along the surface of bedrock. The average bulk density of the A horizon was 1.52. The B horizon exhibited an average bulk density of 1.77. As with site CFP, the bulk density at site RFS appeared to be strongly influenced by the lack of a well-developed root system and the relatively low organic matter content.

Soils of the six forest sites investigated can be grouped into three units based on profile characteristics, surface rock cover and type, and slope location. Sites WFP, 9/3, and PK were located on the west and north slopes of cinder cones or cinder-cone remnants. Surface rock fragments were similar in size and abundance. These sites had an average surface rock cover of 21 percent cobble and 8 percent gravel. Site WGP had an average bulk density significantly lower than sites 9/3 and PK; however, other profile characteristics were so similar that these soils can be grouped together.

Sites WFS and RFS were located on the upper steep slopes of Wahl Knoll and Rudd Knoll, respectively. The surface rock material at these two sites was almost entirely composed of cobble with similar amounts of gravel contained throughout the profile at each site. Both sites contained equivalent amounts of organic matter and root distribution in the profile was similar.

Site CFP had a surface rock cover distinctly different from the other forest sites. Root development in the soil was noticeably low in the B horizon but similar to that of site RFS. The most evident dissimilarity between site CFP and other forest sites, which is the basis for its exclusion from other units, was the textural composition of the B horizon. The B horizon at site CFP had an average clay content of only 31 percent (clay loam) as compared to 44.4 percent clay (clay) for the other sites.

Chemical properties

Forest soils are residual soils developing from basaltic parent materials under the influence of a cold, subhumid to humid climate. There is no evidence suggesting that substantial differences in chemical composition existed between the original parent materials of forest soils and grassland soils. Yet, much greater variations in chemical composition occurred among forest soils than among grassland soils. More variation was observed between forest and grassland sites than between intra-forest or intra-grassland sites. No regional variations in climate exist between

the forests and grasslands; however, microclimatic differences occur, resulting from the influence of topography and vegetative cover, thus exerting a considerable influence over soil formation.

Forest soils are distinctly noncalcareous, showing no visible effervescence with the application of dilute HCl. Atomic absorption analyses revealed an average calcium content of 2175 ppm for forest soils.

Sites WFS, WFP, and CFP showed the highest calcium content of forest soils with 2385 ppm, 2335 ppm, and 2269 ppm, respectively. These sites contained statistically equivalent amounts of calcium but were significantly higher in calcium than sites PK, 9/3, and RFS. In general, higher amounts of calcium occurred in deep soils developing on gentle slopes while lower amounts of calcium were contained in shallow soils developing on steep slopes. Although slope undoubtedly is an important factor influencing drainage characteristics and nutrient losses, calcium abundance in forest soils appears to be related more to soil depth than slope. However, slope is an important factor which must be considered in relation to soil depth.

Regression analysis indicated that calcium decreases in abundance with soil depth (Figure 7). The distribution of calcium in the soil profiles of sites WFS and WFP is considerably above the calcium values predicted by the regression. Site CFP also shows a calcium abundance in the profile above the predicted value of the regression but only to a depth of 30 inches

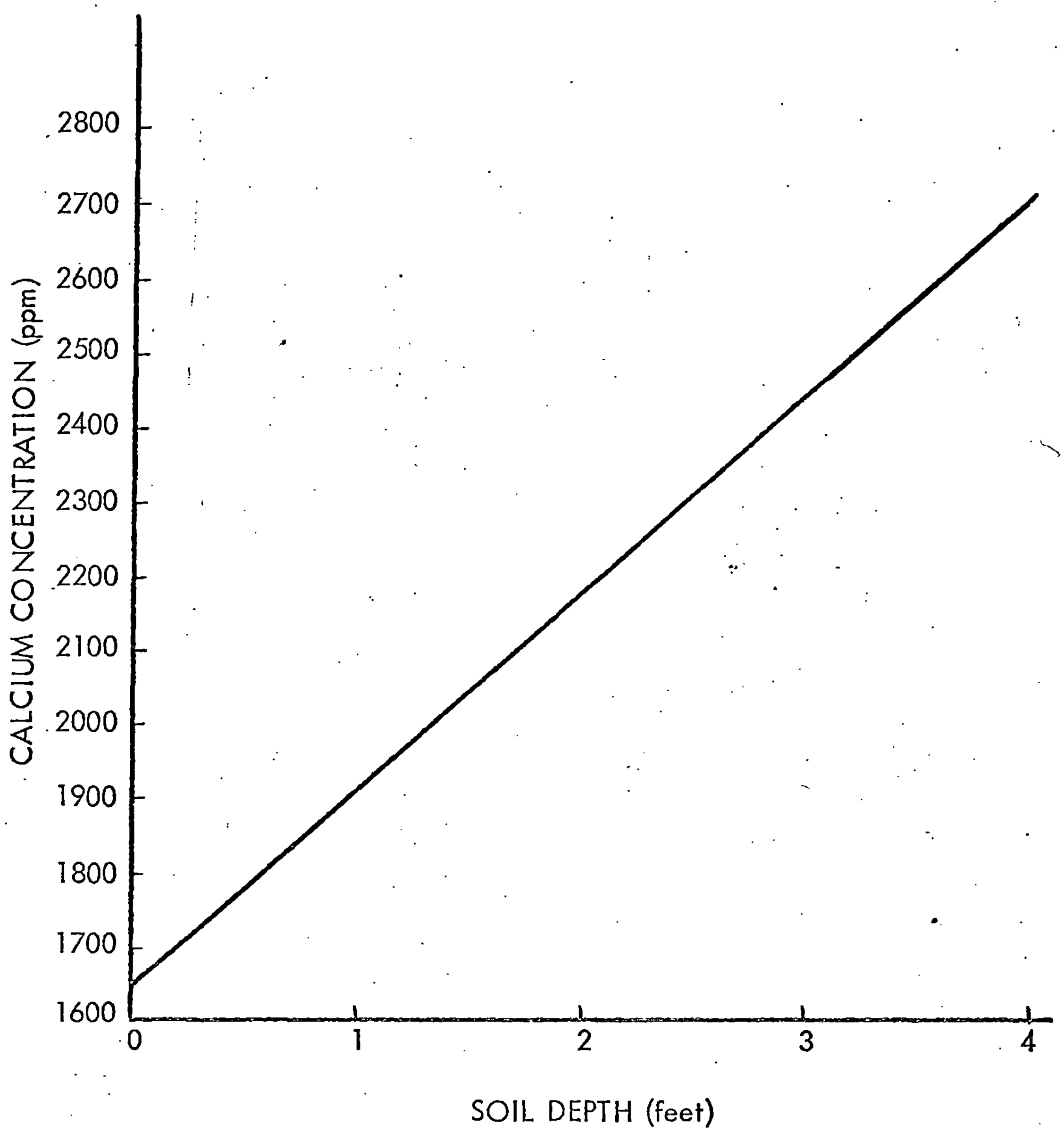

Figure 7. Regression Estimate of Calcium Distribution with Depth in Forest Soils

where the observed abundance is less than the predicted abundance. In the soils at sites WFS, WFP, and CFP, it is suggested that calcium has moved downward as water penetrates into the soil. However, because the soils are deep, most of the water entering the soil does not completely penetrate to bedrock, resulting in the precipitation of carbonates or adsorption of calcium ions by the colloidal soil particles as moisture is depleted from the soil by plant usage or evaporation.

In the shallower soils at sites RFS, 9/3, and PK, because much of the water entering the soil can apparently penetrate the entire profile, calcium dissolved in the soil solution moves downward and is lost in drainage water. Regression analysis shows that the soils at these three sites have an observed calcium content substantially below that predicted by the regression.

The abundance of magnesium in forest soils varied among slightly more than 53 percent of the site comparisons. An average of 890 ppm magnesium occurred in the forest soils, with site CFP showing the highest content (1146 ppm) and site RFS containing the least (647 ppm). The distribution pattern of magnesium fairly closely follows that of calcium. Deeper soils (CFP, WFS, and WFP) contained the highest amounts of magnesium while the shallower soils (PK, 9/3, and RFS) showed the least concentration. It is reasonable to assume that the similarity in the distribution pattern of calcium and magnesium among forest sites is strongly

related to their chemical similarities. Regression analysis shows that magnesium concentration increases at the rate of approximately 14 ppm with each 1-inch increase in depth (Figure 8).

The distribution of potassium among forest sites is more varied than either calcium or magnesium, showing variation among 67 percent of the site comparisons. The average concentration of potassium in forest soils was 8212 ppm. Site CFP exhibited the highest content of potassium with 9324 ppm; site RFS showed the lowest amount with 6976 ppm. Regression analysis shows that potassium increases by approximately 73 ppm with each 1-inch increase in depth (Figure 9).

Potassium is commonly derived from the weathering of potash feldspar. Potash feldspar is the most stable of the feldspars, being moderately persistent in most soils. While the total amount of potassium in soils is normally quite high, the amount considered available to higher plants is generally low. The average amounts of potassium contained in the soils under investigation are within the range of potassium normally occurring in humid region soils. Leaching and utilization by plants generally account for the greatest losses of potassium in the available form. Much of the potassium used by forest vegetation is eventually returned to the soil through the decomposition of organic debris. While leaching losses are probably appreciable in forest soils and account for the high percentage of variation among sites, the loss is not likely to be

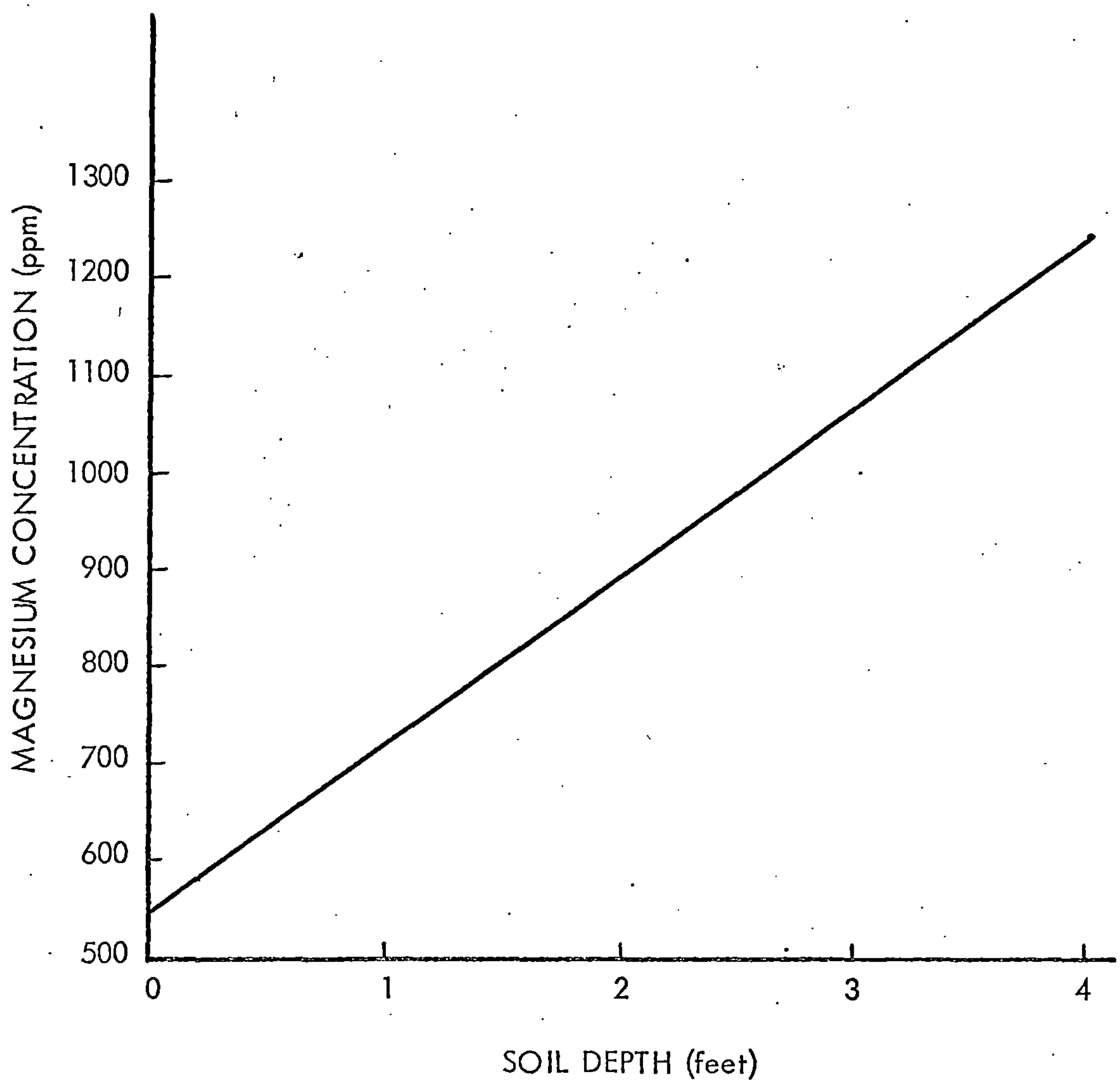

Figure 8. Regression Estimate of Magnesium Distribution with Depth in Forest Soils

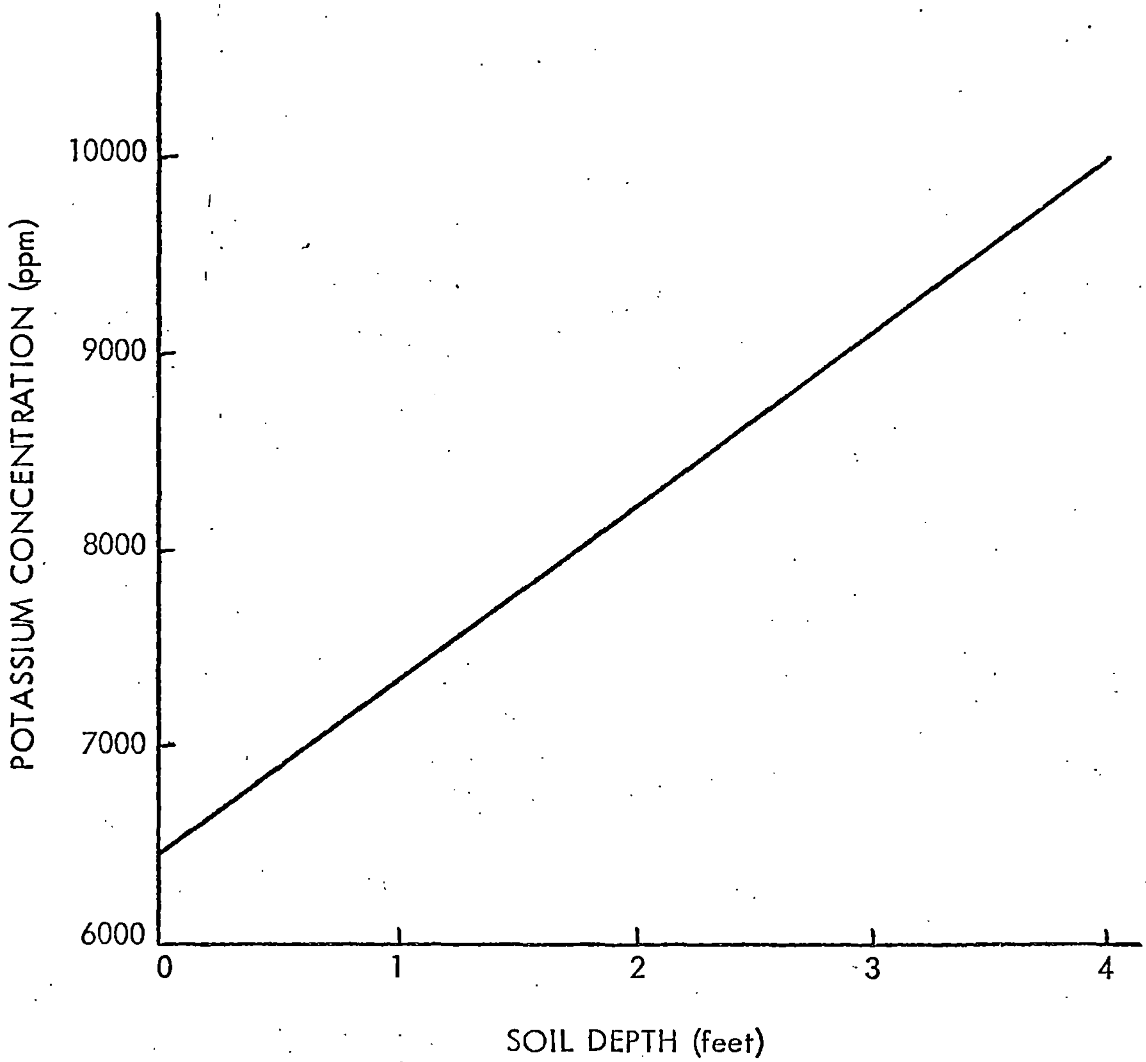

Figure 9. Regression Estimate of Potassium Distribution with Depth in Forest Soils

serious since the removal of potassium-providing minerals by erosion is low. Even where losses may be significant, studies have shown that mycorrhizal fungi supply higher plants with potassium extracted from raw organic material and from the weathering of minerals (Wilde, 1958).

Phosphorus is normally derived from calcium phosphate and organic phosphorus compounds and to a lesser extent iron and aluminum phosphates. Because of its relative insolubility and because it is quickly adsorbed at the undersaturated anion-exchange sites, phosphorus shows low mobility in the soil. To the extent that phosphorus is lost from the soil, it is probably removed by the erosion of phosphorus-bearing minerals in the particulate form with little lost through leaching.

Phosphorus concentration varies among only one-third of the forest sites, generally being more abundant in shallower soils. Concentration of phosphorus ranges from 139 ppm at site CFP to 194 ppm at site RFS, with the average content at all sites being approximately 155 ppm.

Regression analysis indicates that phosphorus concentration decreases in forest soils by approximately 3 ppm with each 1-inch increase in depth (Figure 10) and, while statistical differences occur among sampling sites, their effect on plant growth is probably inconsequential. Wilde (1958) reports that a content of 50 ppm P_2O_5 is sufficient for most forest trees. The decrease in phosphorus concentration with depth can be attributed to the accumulation of phosphorus near the soil surface by the reincorporation

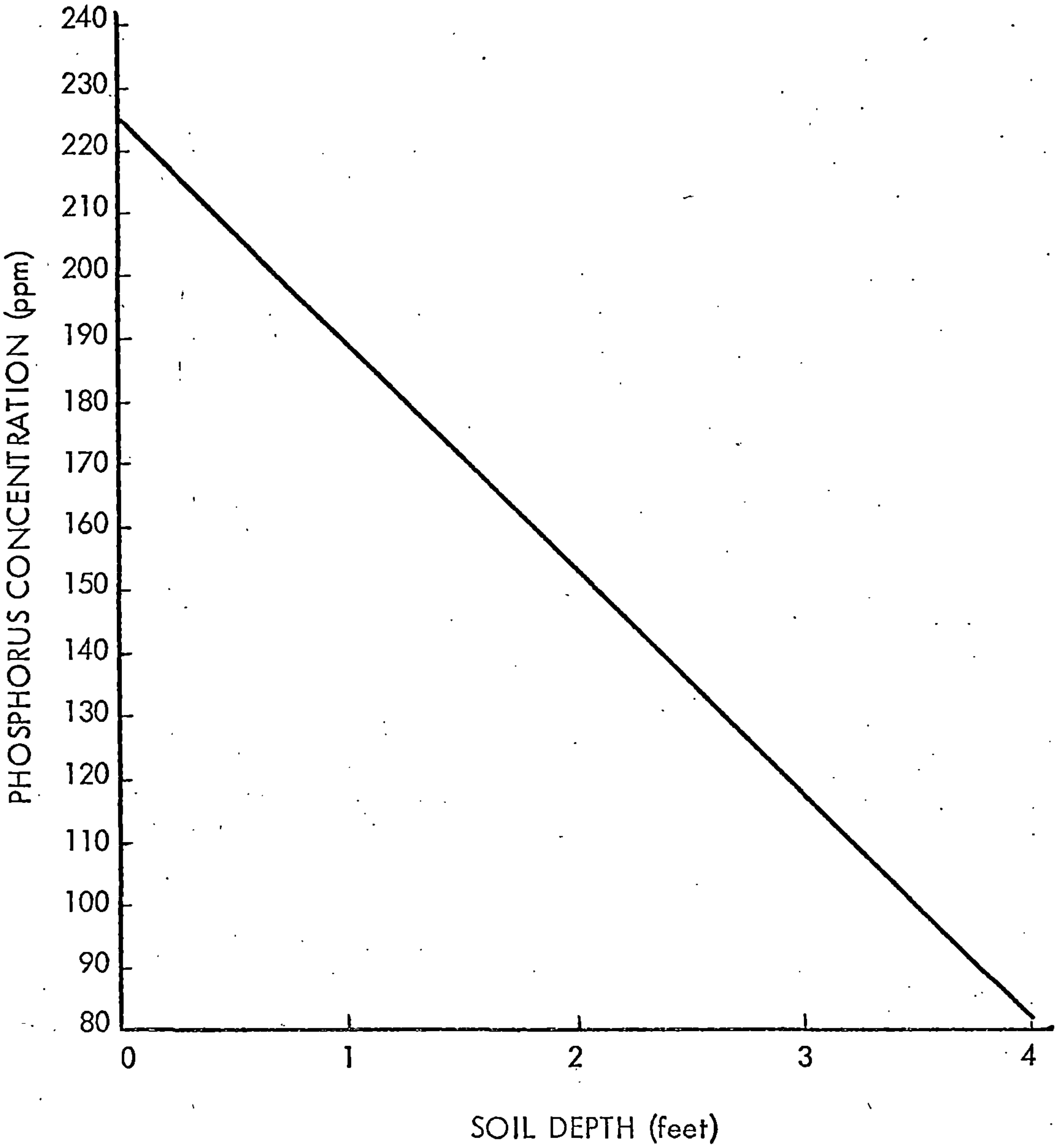

Figure 10. Regression Estimate of Phosphorus Distribution with Depth in Forest Soils

of decomposed forest litter with little subsequent movement downward in the soil profile.

Sodium concentration varies among 67 percent of forest site comparisons, generally being more abundant in deeper soils. The average concentration of sodium in forest soils was 298 ppm, with the highest content at site CFP (348 ppm) and the lowest amount at site PK (241 ppm). The higher amount of sodium in deeper soils is possibly influenced by the apparently lower tendency of these soils to permit deep percolation of water, enhancing the loss of sodium by leaching. The concentration of sodium, as indicated by regression analysis, decreases by approximately 3 ppm with each 1-inch increase in soil depth (Figure 11).

The organic matter and nitrogen concentrations in forest soils do not vary greatly. Only one site (CFP) was shown to contain significantly lower amounts of both nitrogen and organic matter, while only two sites (WFS and RFS) contained significantly lower amounts of organic matter than the site with the greatest concentration (WGP). The average organic matter content of forest soils was 2.97 percent. Nitrogen averaged 0.16 percent in forest soils. As could be expected, there was a fairly close correlation between bulk density and organic matter content. Those soils having higher bulk densities generally contained lower amounts of organic matter.

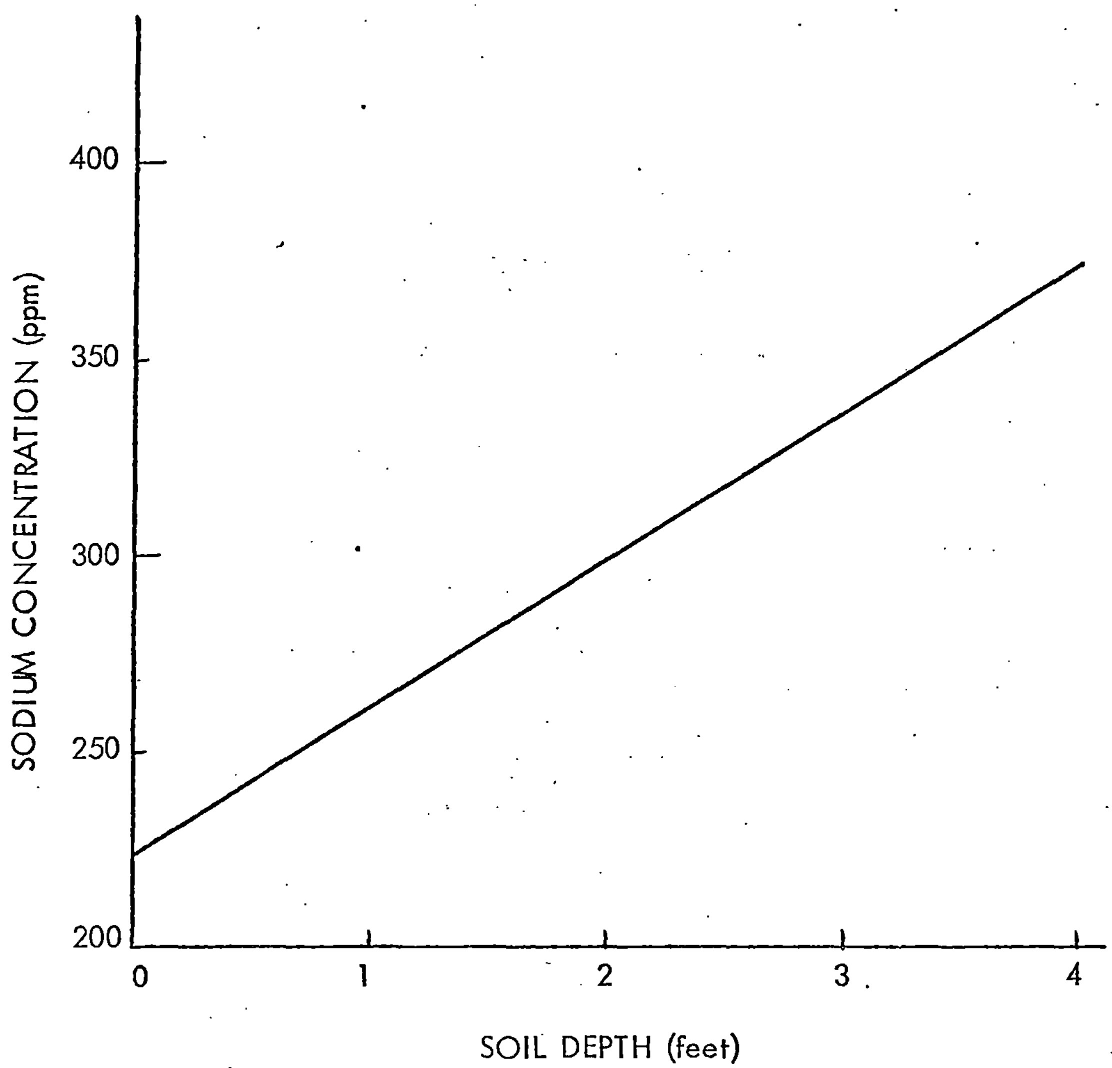

Figure 11. Regression Estimate of Sodium Distribution with Depth in Forest Soils

The average organic matter/nitrogen ratio commonly accepted for mineral soils is 20:1. The forest soils investigated in this study had an average organic matter/nitrogen ratio of approximately 18.7:1. Assuming the rather constant factor of 1.72 for the formation of humus from organic carbon, forest soils averaged about 1.73 percent organic carbon. The carbon/nitrogen ratio thus derived for these forest soils was approximately 10.8:1.

The average pH, as determined by pH meter in a 1:1 soil paste, was 5.8. Variation in the pH of forest soils was statistically significant in approximately 47 percent of the comparisons, being highest at site PK (6.0) and lowest at site CFP (5.64).

Considering only the A horizon of forest soils, shallower soils contain an average of 4.76 percent organic matter and have an average pH of 5.7. Deeper soils exhibit an average organic matter content of 5.2 percent and have an average pH of 5.4. The relationship of organic matter to pH is explained by the formation of organic and inorganic acids during the decomposition of organic matter. The fact that the soils having lower pH values also have higher concentrations of bases is an apparent anomaly. However, the effect of the higher organic matter at sites having higher concentrations of bases, is apparently sufficient to counteract the alkaline effect of the bases.

Table 2 in the section entitled Statistical Analyses summarizes the mean nutrient concentration and pH data employed in statistical calculations.

CHARACTERISTICS OF GRASSLAND-FOREST BOUNDARY SOILS

Profile characteristics

Grassland-forest boundary soils were sampled at five sites to determine the transitional nature of these soils. Boundary sites were located at the interface between grassland and forest at Pool Knoll, Wahl Knoll, and at a forested area approximately 1-1/2 miles north of Crescent Lake near forest site CFP.

In general, boundary soils exhibited physical profile characteristics similar to the adjacent forest while the chemical properties varied somewhat with those of forest and grassland.

Soil profile (composite of sites WS-1, WS-3, WS-5)

A 0 to 6 inches, brown (7.5YR 5/2) gravelly loam; loose; fine to medium granular structure; slightly acid; no visible effervescence with dilute HC1; many grass roots with a few small lateral tree roots; 6 inches thick.

B 6 to 14 inches, reddish brown (5YR 5/3) gravelly clay; slightly hard; weak subangular block structure; slightly acid; no visible effervescence with dilute HC1; many grass roots, fewer tree roots than A above; 4 to 8 inches thick.

Soil profile (site CPB)

A 0 to 6 inches, brown (7.5YR 5/2) gravelly loam; loose; fine to medium granular structure; slightly acid; no visible effervescence with dilute HCl; many grass roots, abundant small tree roots; 6 inches thick.

B 6 to 26 inches, reddish brown (5YR 5/4) gravelly clay; slightly hard; moderate subangular blocky structure; slightly acid; no visible effervescence with dilute HCl; many grass roots, abundant small tree roots; 20 inches thick.

Physical properties

Five pits were excavated at locations representing the boundaries or interface areas between forest and grassland. The boundaries were determined by stretching a 200-foot nylon cord along the bases of the outermost trees of the forested areas. The length of the cord described a polygonal boundary along which a site for pit-excavation was randomly determined. Samples were taken by soil auger at intervals of 50 feet and at depth increments of 6 inches along the entire length of the polygonal boundary and mixed with samples taken from the pit to make a composite sample for laboratory analysis.

The WS sites were located along the ridge crest of Wahl Knoll, extending 200 feet west from the summit. The soil surface at these sites

had an average coverage of 26 percent cobble and 16 percent gravel. Soil depth was 10 to 14 inches. There was almost a complete absence of an organic horizon at these sites with organic debris being limited to very local and small accumulations. The A horizon was a brown gravelly loam from 0-6 inches. The gravel content was approximately 11 percent. The average textural composition was 19 percent clay and 45 percent silt. The A horizon at the WS sites exhibited fine to medium granular structure with fairly weak development. Many grass roots were observed, with tree roots limited to small laterals.

The B horizon (6-14 inches) was a reddish brown gravelly clay exhibiting medium subangular blocky structure, weakly developed. The approximate gravel content of the B horizon was 15 percent. The average textural composition was 51 percent clay and 35 percent silt. Many grass roots were observed throughout the horizon, with a few small lateral tree roots. The lateral tree roots exhibited a horizontal growth habit along the surface of the R horizon.

Site CPB was located at the forest-grassland interface near forest site CFP. Site CPB had an intermittant thin organic horizon with a maximum thickness of 1/2 inch. The soil surface was covered with approximately 11 percent gravel and 5 percent cobble. Small outcrops of basalt were scattered throughout the area but were mostly limited to the adjacent grassland. The A horizon (0-6 inches) was a brown gravelly loam exhibiting

moderately well-developed fine to medium granular structure. The gravel content of the A horizon was approximately 7 percent. The average textural composition was 22 percent clay and 41 percent silt. Many grass roots were observed and abundant small tree roots were present, especially in the upper portion of the horizon.

The B horizon (6-32 inches) was a reddish brown gravelly clay loam. The gravel content of the horizon was approximately 16 percent. The average textural composition was 34 percent clay and 43 percent silt. Many grass roots were distributed rather evenly throughout the horizon and abundant tree roots were present but were sparse in the lower part of the horizon.

Site PKB was located on the northwest forest-grassland interface of Pool Knoll. The surface at this site was covered with approximately 16 percent gravel, with less than 5 percent cobble. An intermittant and thin organic horizon was present, generally less than 1/2 inch in thickness. The A horizon (0-6 inches) was a brown gravelly loam containing approximately 10 percent gravel. The average textural composition was 22 percent clay and 40 percent silt. The horizon exhibited moderately well-developed fine to medium granular structure. Many grass roots were contained throughout the horizon and abundant tree roots were observed.

The B horizon (6-26 inches) was a gravelly, reddish brown clay exhibiting moderately well-developed subangular blocky structure. The

gravel content of the horizon was approximately 10 percent and the average textural composition was 46 percent clay and 39 percent silt. Many grass roots were contained in the horizon along with abundant tree roots in the upper part of the horizon.

Chemical properties

The concentration of nutrients in boundary soils generally falls between that of the grasslands and forests or is slightly higher. Organic matter, nitrogen, calcium, phosphorus, and potassium have intermediate abundances whereas magnesium and sodium are slightly more abundant than their concentrations in forest and grassland soils.

The average calcium concentration in boundary soil (2224 ppm) is intermediate between forest soils (2175 ppm) and grassland soils (2424 ppm).

Fewer statistically significant variations occurred among boundary-grassland soils than among boundary-forest soils. The closer similarity of boundary soils with grassland soils possibly is a reflection of their more similar pH values, with less calcium being lost from the profile as a result of replacement with hydrogen or aluminum ions. A regression analysis for calcium distribution is given in Figure 12.

Magnesium showed little variation among grassland soils and boundary soils with only site CPB having higher concentrations than sites ASW, R, and T. All other comparisons indicated equivalent concentrations of magnesium. Although the average concentration of magnesium in

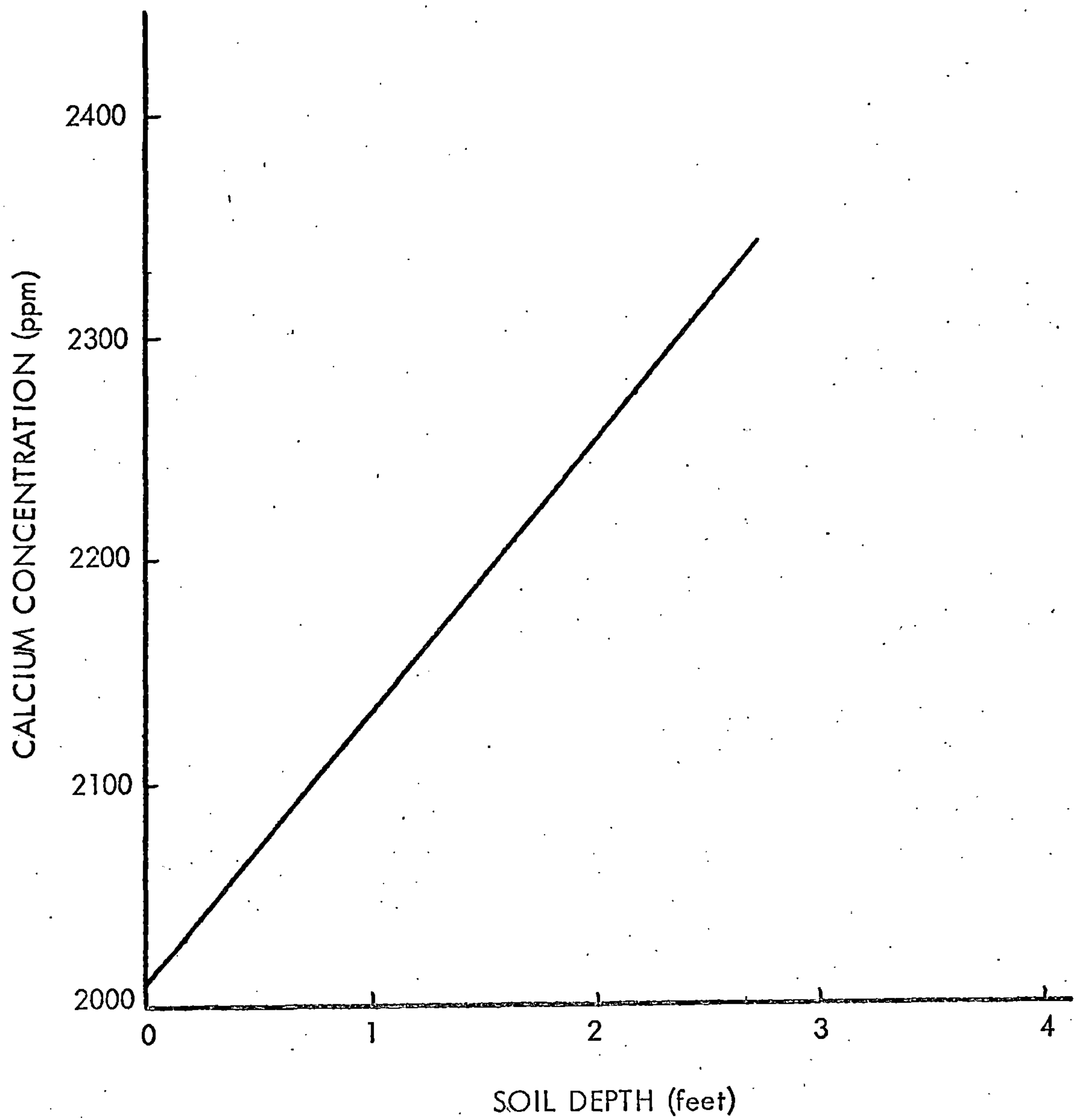

Figure 12. Regression Estimate of Calcium Distribution with Depth in Grassland-Forest Boundary Soils

boundary soils and forest soils was quite similar, a greater number of significant comparisons occurred due to the low concentrations of magnesium at sites 9/3, PK, and RFS. The distribution of magnesium in the profile of boundary soils was quite similar to that of forest soils, increasing in abundance with depth at approximately the same rate, though concentrations might vary considerably (Figure 13).

Potassium abundance in boundary soils shows about the same percentage of variation with grassland soils as with forest soils. Although concentrations vary, potassium increases in abundance with depth (Figure 14) at about the same rate in boundary and forest soils while a striking difference exists between boundary and grassland soils. Potassium is present in greater concentrations in the deeper boundary soils, possibly indicating a substantial reduction in the leaching of potassium. In addition, potassium reincorporated into the soil is likely to be greater at sites CPB and PKB because of the higher amounts of organic debris accumulated at these sites.

The average concentration of phosphorus in boundary soils and grassland soils was nearly the same but phosphorus was clearly more abundant in boundary soils than in forest soils. Whereas grassland soils showed an increase in phosphorus concentration with depth, boundary soils showed a slight decrease (Figure 15) as did forest soils. The apparent increase of phosphorus concentration in the upper layers of boundary and forest soils

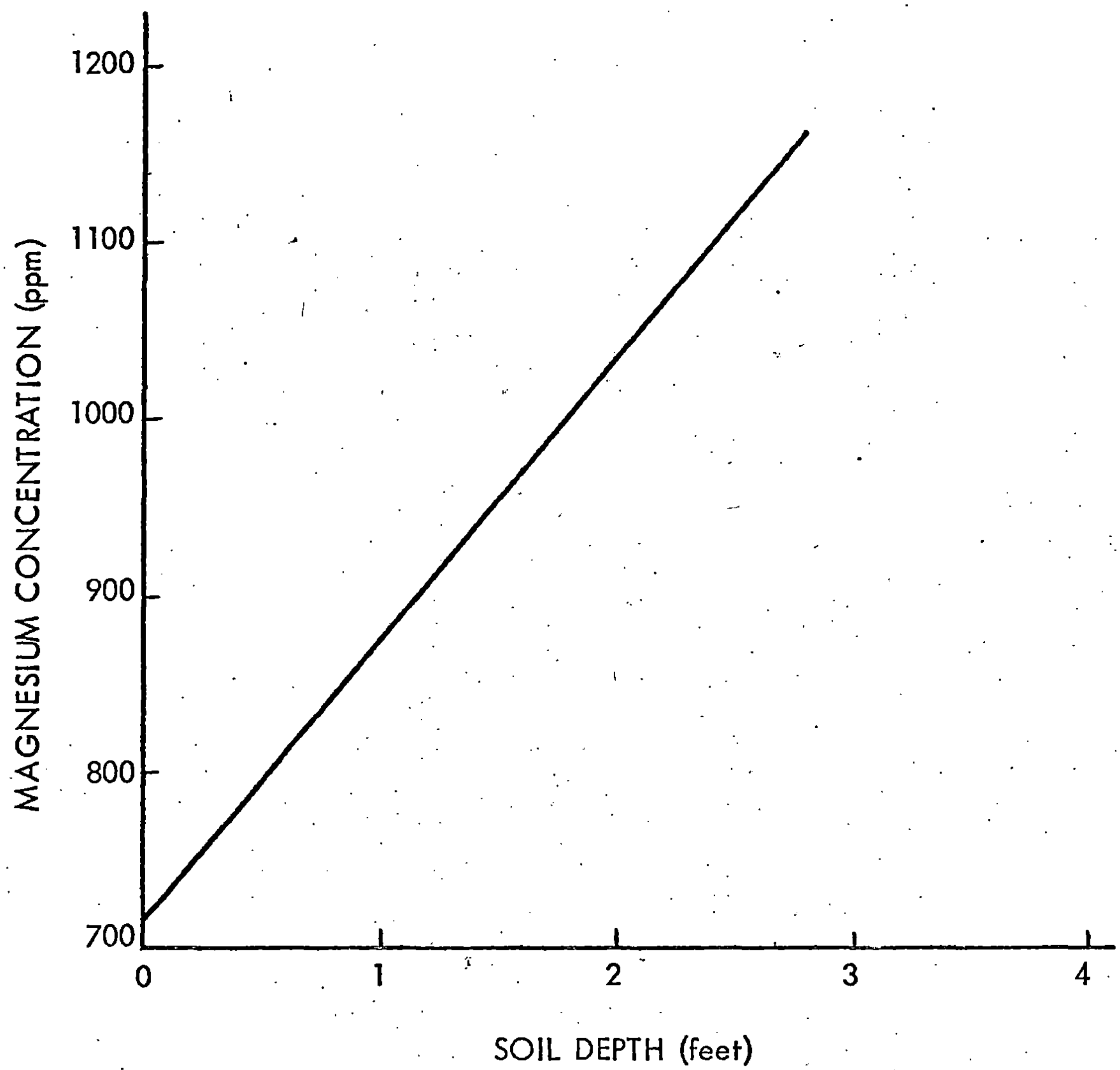

Figure 13. Regression Estimate of Magnesium Distribution with Depth in Grassland-Forest Boundary Soils

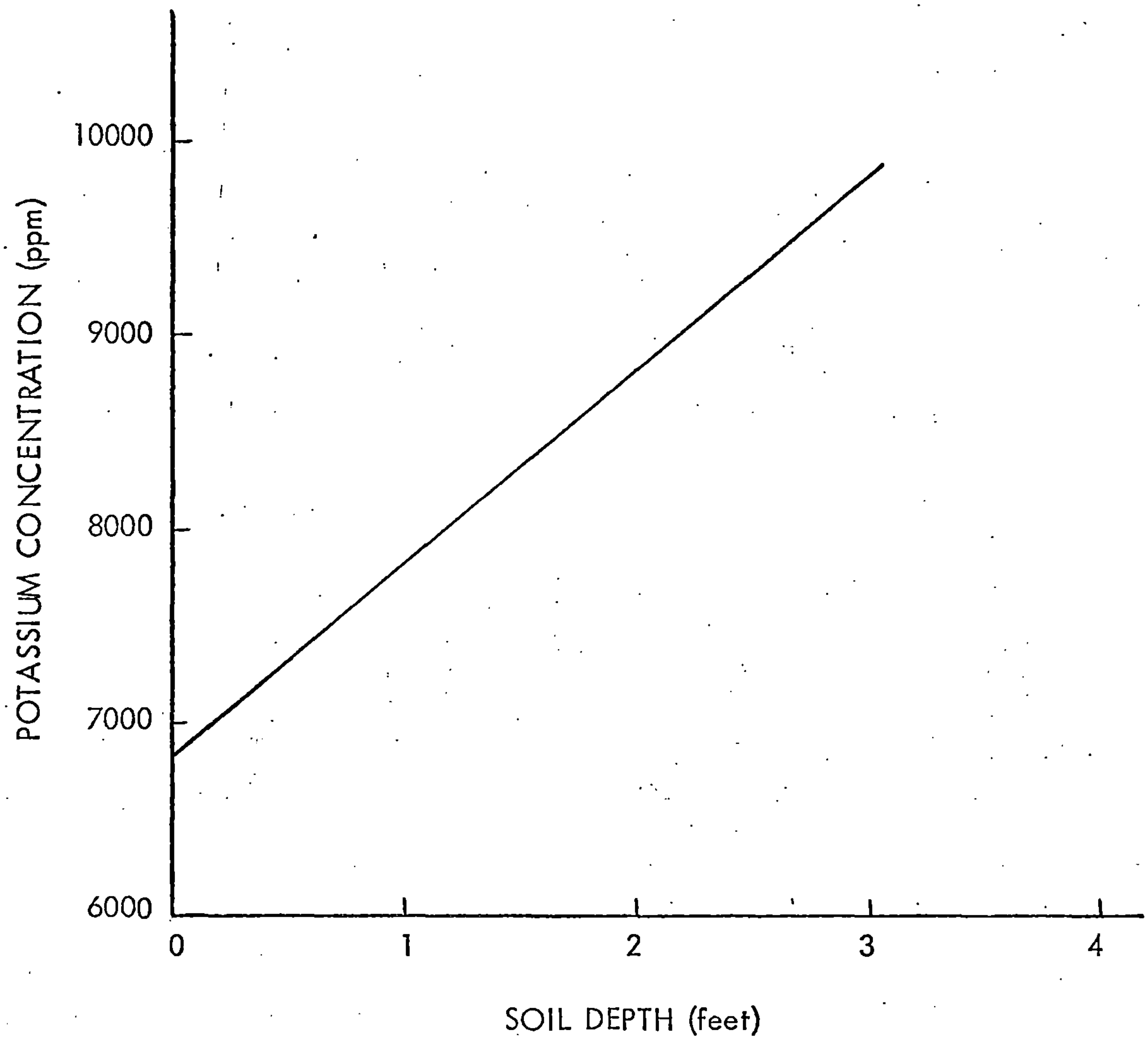

Figure 14. Regression Estimate of Potassium Distribution with Depth in Grassland-Forest Boundary Soils

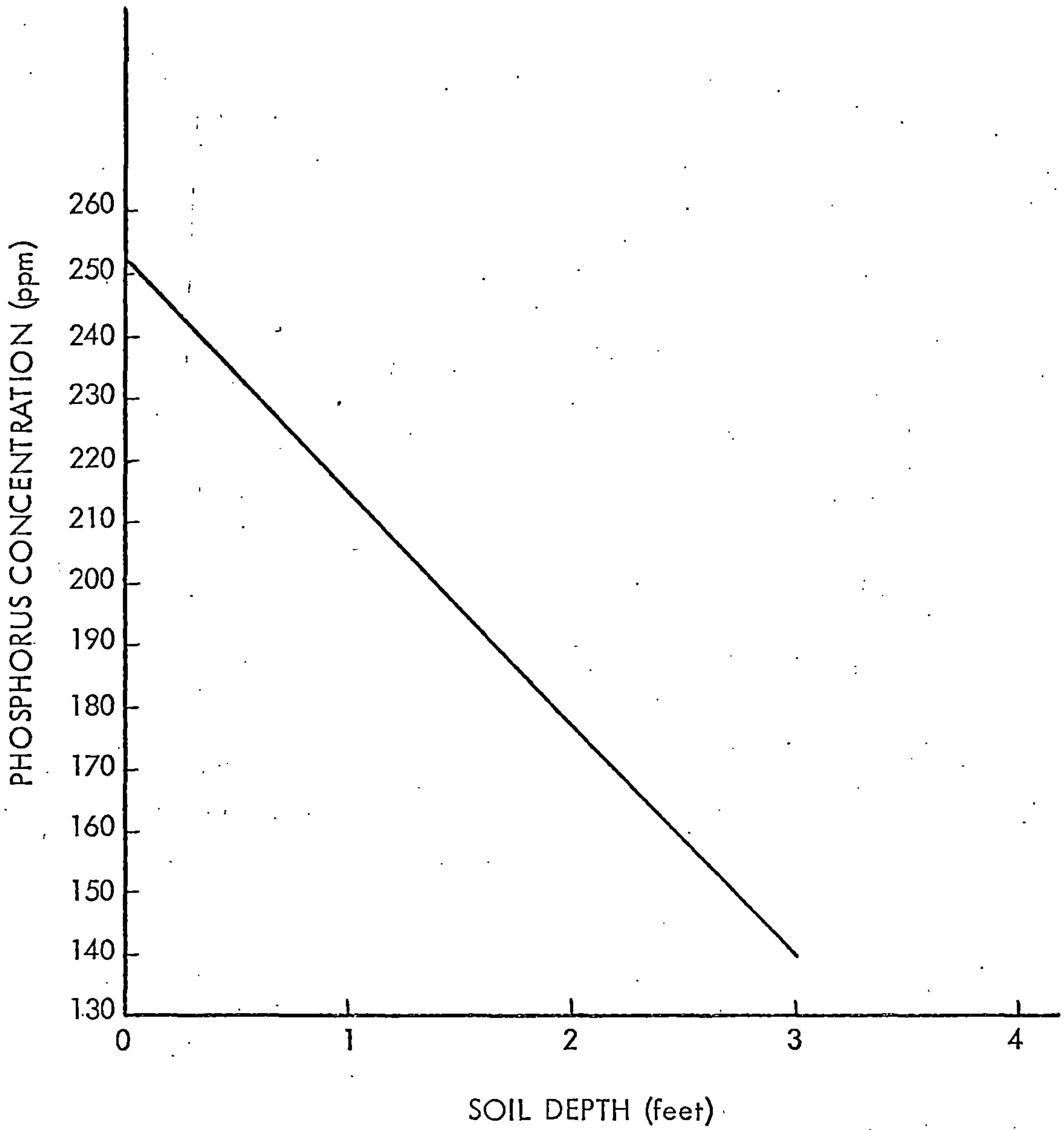

Figure 15. Regression Estimate of Phosphorus Distribution with Depth in Grassland-Forest Boundary Soils

is probably due to the accumulation of phosphorus derived from the decomposition of higher amounts of surface organic debris. The slightly higher rate of decrease in phosphorus concentration with depth in boundary soils as compared to forest soils possibly results from the higher extraction rate of the more numerous grass roots combined with the decomposition of surface organic debris provided by both grass and forest vegetation.

Sodium abundance shows approximately 70 percent variation among comparisons made for boundary and grassland soils as compared to 40 percent for boundary and forest soils. No significant variations occur among boundary soils. It is suggested that the significantly higher concentration of sodium in boundary soils and forest soils results from the lower leaching losses that occur in these generally deeper soils. Regression data (Figure 16) show that sodium increases slightly by approximately 2 ppm with each 1-inch increase in depth.

The average organic matter content of boundary soils is slightly below that of the forest soils and considerably below the average organic matter content of grassland soils. It appears at first glance that boundary soils would exhibit a higher concentration of organic matter since boundary areas would receive organic debris from both forest and grassland. However, neither the grass cover nor the forest vegetation at boundary sites are as dense as in grassland or forest areas, therefore the influx of raw organic matter likely would be reduced. Differences in the balance

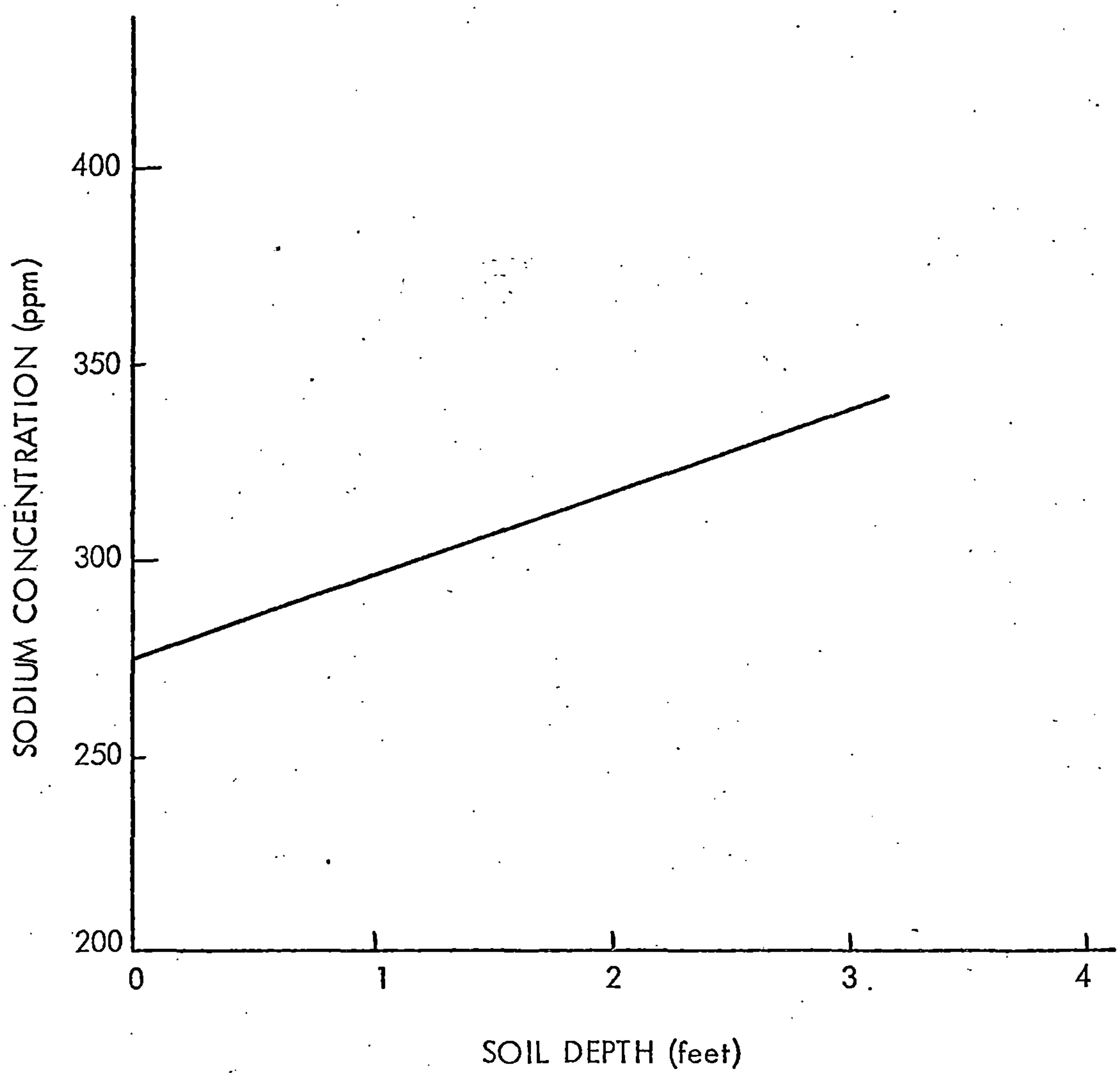

Figure 16. Regression Estimate of Sodium Distribution with Depth in Grassland-Forest Boundary Soils

between replenishment and destruction of humus accounts for the differences in the organic matter in different environments (Hunt, 1972).

The differences that occur among sites with respect to nitrogen abundance display close similarity with those of organic matter and, because of the relationship between the two, this observation could reasonably be predicted.

Approximately 97 percent variation in pH occurs among comparisons involving boundary and forest soils. Only forest site PK (pH 6.0) and boundary site WS-1 (pH 6.05) were statistically equivalent. Variation among grassland and boundary soil pH comparisons showed only 37 percent significance.

Mean nutrient concentrations and pH data employed in analysis of variance calculations, regressions, and comparisons between treatment means are presented in Table 3 of the section entitled Statistical Analyses.

STATISTICAL ANALYSES

Chemical and physical data were statistically analyzed to distinguish variations due to treatments. Three treatments were considered: grassland, forest, and grassland-forest boundary. When treatment data gave larger F ratios than required F ratios, Duncan's Multiple Range Test (Steel and Torrie, 1960) was employed to determine if one treatment was different from another. All data were analyzed at the 5 percent significance level. Tables 1-3 summarize the mean nutrient and pH data employed in all statistical calculations. Table 4 summarizes the analysis of variance data for mean nutrient concentration, pH values, and bulk density.

The results of Duncan's Multiple Range Test comparisons are presented in Figures 17-24. In these comparisons, "g" (grassland), "f" (forest), and "i" (interface) indicate which treatment mean was significantly higher. Blank spaces indicate no significance between treatment means.

Regression analyses were performed to determine the overall distribution of chemical nutrients and variation of bulk density with depth. The results of the regression analyses are presented throughout the text of this paper.

Table 1. Mean Nutrient Concentration
and pH Data for Grassland Soils

Site	Ca ppm	Mg ppm	K ppm	P ppm	Na ppm	N %	OM %	pH
WGP	2477	922	7946	221	293	0.1019	1.92	6.20
WK	2526	880	7625	203	244	0.1199	2.28	6.18
T	2442	817	7771	209	226	0.2012	3.82	6.15
ASW	1829	832	7366	231	258	0.1596	3.27	6.50
R	2301	826	8291	208	243	0.3055	5.78	6.10
CS-1	2471	888	8479	180	237	0.2137	3.67	6.30
CS-2	2576	907	8277	176	292	0.1759	3.04	6.30

Table 2. Mean Nutrient Concentration
and pH Data for Forest Soils

Site	Ca ppm	Mg ppm	K ppm	P ppm	Na ppm	N %	OM %	pH
WFS	2385	873	8504	146	285	0.1418	2.67	5.84
WFP	2335	854	7817	157	324	0.1422	4.10	5.68
PK	1965	773	7561	149	241	0.1389	3.64	6.00
CFP	2269	1146	9324	139	348	0.0763	1.52	5.64
9/3	1890	820	7933	176	268	0.1976	3.62	5.78
RFS	1667	647	6976	194	269	0.1762	2.66	5.73

Table 3. Mean Nutrient Concentration and pH Data for Boundary Soils

Site	Ca ppm	Mg ppm	K ppm	P ppm	Na ppm	N %	OM %	pH
PKB	2090	940	8212	191	288	0.1370	2.47	6.40
CPB	2152	992	8460	190	295	0.1377	2.47	6.25
WS-1	2377	807	7545	225	312	0.1697	4.11	6.05
WS-3	2417	820	7679	228	321	0.1602	3.37	6.55
WS-5	2363	806	7515	133	314	0.1650	3.45	6.50

Table 4. Analyses of Variance of Chemical and Physical Data

Property or Nutrient	Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio	Significance Level
Calcium	Treatments	2	4866359.747	2433179.874	197.10	0.05
	Error	282	3481124.000	12344.400		
	Total	284	8347483.747			
Magnesium	Treatments	2	1016541.189	508270.594	101.32	0.05
	Error	282	1414627.400	5016.409		
	Total	284	2431168.589			
Phosphorus	Treatments	2	81349.426	40674.713	78.52	0.05
	Error	282	146079.100	518.010		
	Total	284	227428.526			
Sodium	Treatments	2	137275.531	68637.765	167.18	0.05
	Error	282	115778.300	410.561		
	Total	284	253053.831			
Potassium	Treatments	2	27429608.490	13714804.250	88.46	0.05
	Error	282	43718688.000	155030.808		
	Total	284	71148296.490			

Table 4 (continued). Analyses of Variance of Chemical and Physical Data

Property or Nutrient	Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio	Significance Level
Nitrogen	Treatments	2	0.41546	0.207	87.419	0.05
	Error	282	.06701	0.002		
	Total	284	1.08556			
pH	Treatments	2	6.593	3.296	212.48	0.05
	Error	282	4.375	0.015		
	Total	284	10.968			
Bulk Density	Treatments	2	1.117	0.558	77.27	0.05
	Error	282	2.039	0.007		
	Total	284	3.156			
Organic Matter	Treatments	2	89.905	44.952	72.93	0.05
	Error	282	173.799	0.616		
	Total	284	263.704			

	CS 2	WK	WGP	CS 1	T	R	ASW
WFS							f
WFP	g	g					f
CFP	g	g	g				
PK	g	g	g	g	g	g	
9/3	g	g	g	g	g	g	
RFS	g	g	g	g	g	g	

Figure 17a. Duncan's Multiple Range Test for Calcium Variation Between Grassland and Forest Soils

	WFS	WFP	CFP	PK	9/3	RFS
WS-3				l	l	l
WS-1				l	l	l
WS-5				l	l	l
CPB	f	f		l	l	l
PKB	f	f	f		l	l

Figure 17b. Duncan's Multiple Range Test for Calcium Variation Between Forest and Boundary Soils

	CS 2	WK	WGP	CS 1	T	R	ASW
WS-3							l
WS-1							l
WS-5							l
CPB	g	g	g	g	g		l
PKB	g	g	g	g	g	g	l

Figure 17c. Duncan's Multiple Range Test for Calcium Variation Between Grassland and Boundary Soils

	WGP	CS 2	CS 1	WK	ASW	R	T
CFP	f	f	f	f	f	f	f
WFS							
WFP							
9/3							
PK	g	g		g			
RFS	g	g	g	g	g	g	g

Figure 18a. Duncan's Multiple Range Test for Magnesium Variation Between Grassland and Forest Soils

Figure 18b. Duncan's Multiple Range Test for Magnesium Variation Between Forest and Boundary Soils

	CFP	WFS	WFP	9/3	PK	RFS
CPB	f		l	l	l	l
PKB	f				l	l
WS-3	f					l
WS-1	f					l
WS-5	f					l

	WGP	CS 2	CS 1	WK	ASW	R	T
CPB					l	l	l
PKB							
WS-3							
WS-1							
WS-5							

Figure 18c. Duncan's Multiple Range Test for Magnesium Variation Between Grassland and Boundary Soils

	CS 1	R	CS 2	WGP	T	WK	ASW
CFP	f	f	f	f	f	f	f
WFS					f	f	f
9/3							
WFP							
PK		g	g				
RFS	g	g	g	g	g	g	

Figure 19a. Duncan's Multiple Range Test for Potassium Variation Between Grassland and Forest Soils

	CFP	WFS	9/3	WFP	PK	RFS
CPB	f			l	l	l
PKB	f					l
WS-3	f	f				
WS-1	f	f				
WS-5	f	f				

Figure 19b. Duncan's Multiple Range Test for Potassium Variation Between Forest and Boundary Soils

	CS 1	R	CS 2	WGP	T	WK	ASW
CPB					l	l	l
PKB							l
WS-3			g				
WS-1		g	g				
WS-5	g	g	g				

Figure 19c. Duncan's Multiple Range Test for Potassium Variation Between Grassland and Boundary Soils

	ASW	WGP	T	R	WK	CS 1	CS 2
RFS							
9/3	g	g	g				
WFP	g	g	g	g	g		
PK	g	g	g	g	g		
WFS	g	g	g	g	g		
CFP	g	g	g	g	g	g	g

Figure 20a. Duncan's Multiple Range Test for Phosphorus Variation Between Grassland and Forest Soils

Figure 20b. Duncan's Multiple Range Test for Phosphorus Variation Between Forest and Boundary Soils

	RFS	9/3	WFP	PK	WFS	CFP
WS-5		I	I	I	I	I
WS-3		I	I	I	I	I
WS-1		I	I	I	I	I
PKB				I	I	I
CPB					I	I

	ASW	WGP	T	R	WK	CS 1	CS 2
WS-5							I
WS-3							I
WS-1							I
PKB							
CPB	g						

Figure 20c. Duncan's Multiple Range Test for Phosphorus Variation Between Grassland and Boundary Soils

	WGP	CS 2	ASW	WK	R	CS 1	T
CFP	f	f	f	f	f	f	f
WFP	f	f	f	f	f	f	f
WFS				f	f	f	f
RFS							f
9/3	g						f
PK	g	g					

Figure 21a. Duncan's Multiple Range Test for Sodium Variation Between Grassland and Forest Soils

Figure 21b. Duncan's Multiple Range Test for Sodium Variation Between Forest and Boundary Soils

	CFP	WFP	WFS	RFS	9/3	PK
WS-3	f			l	l	l
WS-5	f			l	l	l
WS-1	f			l	l	l
CPB	f	f			f	f
PKB	f	f				l

	WGP	CS 2	ASW	WK	R	CS 1	T
WS-3			l	l	l	l	l
WS-5			l	l	l	l	l
WS-1			l	l	l	l	l
CPB			l	l	l	l	l
PKB				l	l	l	l

Figure 21c. Duncan's Multiple Range Test for Sodium Variation Between Grassland and Boundary Soils

	R	CS 1	T	CS 2	ASW	WK	WGP
9/3	g						
RFS	g						
WFP	g		g				
WFS	g		g				
PK	g		g				
CFP	g	g	g	g	g		

Figure 22a. Duncan's Multiple Range Test for Nitrogen Variation Between Grassland and Forest Soils

	9/3	RFS	WFP	WFS	PK	CFP
WS-1						l
WS-5						l
WS-3						
CPB						l
PKB						

Figure 22b. Duncan's Multiple Range Test for Nitrogen Variation Between Forest and Boundary Soils

	R	CS 1	T	CS 2	ASW	WK	WGP
WS-1	g						
WS-5	g						
WS-3	g						
CPB	g		g				
PKB	g		g				

Figure 22c. Duncan's Multiple Range Test for Nitrogen Variation Between Grassland and Boundary Soils

	R	T	CS 1	ASW	CS 2	WK	WGP
WFP	g						
PK	g						
9/3	g						
WFS	g	g	g				
RFS	g	g	g				
CFP	g	g	g				

Figure 23a. Duncan's Multiple Range Test for Organic Matter Variation Between Grassland and Forest Soils

Figure 23b. Duncan's Multiple Range Test for Organic Matter Variation Between Forest and Boundary Soils

	WFP	PK	9/3	WFS	RFS	CFP
WS-1						l
WS-5						l
WS-3						l
PKB						
CPB						

	R	T	CS 1	ASW	CS 2	WK	WGP
WS-1	g					l	l
WS-5	g						l
WS-3	g						
PKB	g	g					
CPB	g	g					

Figure 23c. Duncan's Multiple Range Test for Organic Matter Variation Between Grassland and Boundary Soils

	ASW	CS 1	CS 2	WGP	WK	T	R
PK	g	g	g	g	g	g	
WFS	g	g	g	g	g	g	g
9/3	g	g	g	g	g	g	g
RFS	g	g	g	g	g	g	g
WFP	g	g	g	g	g	g	g
CFP	g	g	g	g	g	g	g

Figure 24a. Duncan's Multiple Range Test for pH Variation Between Grassland and Forest Soils

Figure 24b. Duncan's Multiple Range Test for pH Variation Between Forest and Boundary Soils

	PK	WFS	9/3	RFS	WFP	CFP
WS-3	l	l	l	l	l	l
WS-5	l	l	l	l	l	l
PKB	l	l	l	l	l	l
CPB	l	l	l	l	l	l
WS-1		l	l	l	l	l

	ASW	CS 1	CS 2	WGP	WK	T	R
WS-3			l	l	l	l	l
WS-5				l	l	l	l
PKB				l	l	l	l
CPB							
WS-1							

Figure 24c. Duncan's Multiple Range Test for pH Variation Between Grassland and Boundary Soils

	WGP	ASW	T	WK	CS 1	CS 2	R
CFP	f		f	f	f	f	f
RFS							f
9/3							f
WFS							f
PK							f
WFP	g	g	g	g			f

Figure 25a. Duncan's Multiple Range Test for Bulk Density Variation Between Grassland and Forest Soils

Figure 25b. Duncan's Multiple Range Test for Bulk Density Variation Between Forest and Boundary Soils

	CFP	RFS	9/3	WFS	PK	WFP
CPB	f					l
PKB	f					l
WS-5	f	f	f	f		
WS-3	f	f	f	f	f	
WS-1	f	f	f	f	f	

	WGP	ASW	T	WK	CS 1	CS 2	R
CPB						l	l
PKB							l
WS-5							
WS-3							
WS-1							

Figure 25c. Duncan's Multiple Range Test for Bulk Density Variation Between Grassland and Boundary Soils

EXPERIMENTAL PROCEDURES AND METHODS

Site selection

Because off-road vehicle traffic in the Apache National Forest is prohibited, certain accessible areas were selected which were considered to be representative of the soils to be investigated. With the aid of aerial photographs and topographic maps, sampling sites within the accessible areas were randomly selected. For linear transects, the direction was predetermined to be perpendicular to slope (map) contours but the starting point was randomly determined.

Sampling methods

Where pits were excavated, soil samples were taken, generally at depth increments of six inches, directly from the pit. Along linear transects, soil samples were taken by soil auger, barrel-type auger, or shovel, generally at 6-inch increments. Where larger samples were required, several auger samples of corresponding increments at the same site were combined to form a composite sample.

Soil samples extracted for the determination of bulk density were taken in clod form or were extracted by core tube. Soils which, when dry, did not permit the extraction of clods were first moistened before clod samples were taken.

Depth probes were taken in the general area of all sampling sites with the aid of a pointed steel rod (0.5 inches in diameter by 5 feet long), calibrated in inches. The rod was driven into the soil by hammer until complete resistance was encountered. Depth probes were generally conducted along the circumference of a circle with the sampling site at the center or along linear transects perpendicular and parallel to slope (map) contours.

The estimation of surface rock-fragment coverage was facilitated by the use of a 24-inch square quadrat constructed of one-quarter inch steel rod. The average of at least two estimations was accepted as being a reasonable estimate of surface rock coverage.

Laboratory analyses

Organic carbon was determined by the modified Walkley-Black method. A weighed quantity of soil, ground to pass a 0.5 mm sieve, was transferred to a 500-ml Erlenmeyer flask and 10 ml of 1 N potassium dichromate was added. Twenty ml of concentrated sulfuric acid was rapidly added, directing the stream into the solution. The contents were swirled by hand for one minute, then allowed to cool slowly for 30 minutes. After the elapsed time, 200 ml of distilled water was added to the flask, with four drops of O-phenanthroline indicator.

Titration of the solution by 0.5 N ferrous sulfate solution was then carried out to the solution turned red, indicating the end point of the titration.

The percentage of organic carbon was calculated from the formula:

$$\% C + \frac{(\text{Meq } K_2Cr_2O_7 - \text{Meq } FeSO_4 \text{ required}) \times 0.69}{\text{Sample weight (corrected for oven-dry weight)}}$$

The approximate percentage of organic matter was calculated by multiplying the % C by 1.72.

Total nitrogen was determined by the Kjeldahl method. Ten grams of soil were placed in a dry Kjeldahl flask and 30 ml of concentrated sulfuric acid was added. A package of catalyst mixture was placed in the flask and the flask was immediately placed on the digestion rack of the apparatus. The flask was turned at 10-minute intervals until digestion was complete (3-4 hours). The flask was then allowed to cool in an ice bath for approximately 10 minutes.

Distillation was carried out by placing 50 ml of saturated boric acid in a 500-ml Erlenmeyer flask. Three drops of brom-creosol green indicator were added to the boric acid. Two hundred ml of distilled water was slowly added to the contents of the Kjeldahl flask. Then, 75 ml of 50-percent sodium hydroxide solution was carefully poured down the neck of the Kjeldahl flask, forming a layer in the bottom of the flask. One teaspoon of granular zinc was then added to the flask to prevent bumping and the flask was immediately connected to the distillation apparatus while swirling to mix the contents of the flask. The distillation was continued until approximately 150 ml of the liquid had distilled over.

Titration was then carried out with standardized sulfuric acid until the light-orange color appeared, indicating the end point of the titration.

The percentage of nitrogen was calculated from the formula:

$$\% N = \frac{(\text{Meq } H_2SO_4 \times \text{Normality} \times 0.014 \times 100}{\text{Sample weight (corrected for oven-dry weight)}}$$

Phosphorus was determined colormetrically by the "stannouschloride-reduce molybdophosphoric blue color method, in a hydrochloric acid system" (Black and others, 1965; Jackson, 1958).

Five grams of moist soil was suspended in 100 ml of $NaHCO_3$ extraction solution adjusted to pH 8.5 and shaken for 30 minutes with one teaspoon of carbon black in a 500-ml Erlenmeyer flask. The solution was then filtered.

A series of standard solutions was prepared containing 10, 20, 30, 40, and 50 ppm phosphorus. The molybdophosphoric blue color was developed by adding 10 ml of chloromolybdic acid reagent to the standard solutions. Then, five drops of chlorostannous acid reductant is added to the standard solution and thoroughly mixed. After five minutes, the color was read photometrically (Bausch & Loumb Spectronic 20 colorimeter) at the 660-millimicron light setting with a red filter. A callibration curve was prepared from the standard solutions.

The molybdophosphoric blue color was developed in the phosphorus extract identically to that of the standard solutions and the color read by the

colorimeter. The phosphorus concentration in the soil sample was then determined graphically from the callibration curve.

Total calcium, magnesium, potassium, and sodium concentrations were determined by atomic absorption spectrophotometry. Analytical procedures for the determination of these elements were taken or adapted from the Varian Tectron manual entitled "Analytical Methods for Flame Spectroscopy." Determinations were made on a Varian Atomic absorption spectrophotometer, model 1100.

Mechanical analyses for soil texture determinations were made by the Bouyoccous hydrometer method. When organic carbon determinations showed that the soil contained 2 percent or more organic matter, the soil sample was first treated with hydrogen peroxide and heated over a water bath to oxidize the organic matter. The soil sample was put into a blender with 5 ml of hexametaphosphate and approximately 500 ml of distilled water and stirred for three minutes. The contents of the blender cup were completely removed and placed in a tall graduated cylinder designed for mechanical analyses. The contents of the cylinder were stirred for one minute and the stirrer removed. After 20 seconds had elapsed, the hydrometer was slowly lowered into the cylinder and a reading was taken at exactly 40 seconds and recorded. After two hours, a second reading was taken and the percentages of sand, silt, and clay were calculated.

Bulk density determinations were made by the wax-coated clod method or were determined from weighed cores taken by core tube with a known volume.

The pH of soil samples was determined by electronic pH meter in a 1:1 soil paste.

Mycorrhizal fungi were collected from small feeder roots of pine trees. In the laboratory, the mycorrhizal roots were disinfected with a 1-percent solution of sodium hypochlorite for 20 minutes (Stevens, 1974). After rinsing thoroughly with distilled water, small pieces of the mycorrhiza were plated on potato-glucose agar in a petri dish and grown for two weeks.

An extract of grassland soil was prepared by leaching 100 ml of distilled water through a 25-gram soil sample. The leachate was adjusted to pH 4.0 with 0.1 N HCl to retard bacterial growth. Five ml of the leachate was placed on potato-glucose agar with 0.1 g soil. The culture was compared to that produced by the mycorrhizal fungi after 14 days. Microscopic examination did not reveal the growth of any fungi similar to that of the mycorrhiza culture.

DISCUSSION

Statistically significant variations were shown to exist in the chemical and physical properties of high-elevation grasslands and adjacent forests of the study area. While significant differences occur, the characteristics of these soils are generally within the range commonly expected for subhumid to humid region mineral soils. The major nutrient-element composition of these soils suggests that encroachment of trees into grassland areas is not seriously retarded or prevented by variations in the relative abundances of the essential nutritional elements for which analyses were conducted or by differences in the physical properties of the soils. Although statistical differences do occur, they are probably not sufficient to be detrimental to the growth of vegetation.

It is recognized that differences in the concentrations of nutritional elements for which analyses were not conducted could seriously affect the growth of vegetation and inhibit the encroachment of trees into grassland areas. Wilde (1958) reports that boron, manganese, zinc, copper, and molybdenum appear to be of primary importance in the growth of trees.

To the extent that elemental concentrations vary among the study area soils, they appear to be closely associated with local variations in

topography. In general, nutrient-element concentrations are lower in shallow soils, regardless of the topography on which the soils are developing. This is probably due to the ease with which precipitation is able to penetrate the entire profile, carrying with it nutrients in solution which may be lost by drainage.

Soil formation is greatly affected by surface slope which influences the differential distribution of atmospheric agencies. The most significant influence of slope is to increase the rate of surface runoff and enhance erosion. While no evidence of serious erosion was observed, surface runoff, especially on steep slopes, is undoubtedly an important factor in determining the extent to which nutrient-bearing soil particles in the upper soil layers are lost or redistributed by erosion. Those nutritional elements, primarily phosphorus, which are normally concentrated in the upper soil layers are especially subject to removal as the minerals that contain them are washed away in particulate form by surface runoff.

Slope also profoundly affects the moisture balance of soils by influencing the rate of runoff. The infiltration rates of study area soils (2.5-5.0 in./hr.) combined with the amounts and seasonal distribution of precipitation and vegetative cover suggests that significant surface runoff is limited to areas with barren soils or steep grassland slopes when storm intensity exceeds the infiltration rate.

While the amount of precipitation reaching the soil surface is greater in grassland areas than forest areas due to the ability of the respective vegetation types to intercept precipitation, grassland soils exhibit a predictably lower moisture content. The lower moisture content of grassland soils is due to the increased exposure of the soils to moisture-depleting processes, especially evaporation and drainage.

The relative amounts of snow retained by the grasslands and forests also influence the moisture regimes of the respective areas. The winter snow cover in grassland areas is often thin, or absent, because of the removal of snow in the open areas by wind with subsequent sublimation. Snow removed from the open grasslands is collected and retained by the adjacent forest areas. During the Spring thawing period, both forest and grassland soils are locally saturated with moisture. Surface runoff is evident in both vegetation types. Where the surface remains frozen, surface runoff may be excessive and carry with it organic debris or soil particles, some of which may be contained in ice fragments freed during thawing. The rate of thawing is less in forested areas due to the interception of solar radiation by the forest canopy. Because the thawing rate is lower, moisture has a greater opportunity to infiltrate the soil but, because the amount of snow melt is substantially more than in grassland areas, surface runoff is greater.

Slope is also of major importance in its influence on soil formation, soil microflora and microfauna, and the development of characteristic vegetation. Northern slopes in all seasons receive the least amount of solar radiation. On southern slopes, up to a certain steepness, solar radiation increases in comparison with the amount received by horizontal land surfaces. Soil microorganisms are significantly affected by the intake of solar warmth. Vegetation is particularly sensitive to the shape of slopes and its influence on microclimatic variations.

In addition to the effects manifested by landform, precipitation, and solar radiation, the distribution and type of vegetation may be enhanced or retarded by the development of symbiotic plant-microorganism associations. Such an association exists between the trees in the forested areas of the study area and mycorrhizal fungi. Soil-fungi cultures and ocular examination revealed that mycorrhizal fungi are absent in grassland soils but are present in forest soils in association with coniferous trees. Ectotrophic mycorrhiza occur on the roots of pine trees as branched, nodule-like swellings. While the abundance of nutrient-elements in study area soils is within the range normally expected of subhumid to humid regions, their abundance lies near the lower portion of the range. Wilde (1958) reports that the abundance of mycorrhizal roots bears a close correlation with soil fertility. The development of mycorrhiza is possibly controlled by the concentration and balance of nutrients within the host plant and by the ability

of the root tissues to resist penetration by the fungal mycelia. The utilization of nutrients locked in chemically combined mineral forms is facilitated by the high dissolving power and large absorbing surface of fungal mycelia. Researchers have demonstrated that trees, with the help of mycorrhizal fungi, may absorb potassium from unweathered feldspar and other potassium-bearing minerals.

That mycorrhizal fungi are of practical significance has been demonstrated by silviculturalists working in grassland soils (Wilde, 1958). Observations by these researchers established with certainty that grassland soils do not contain mycorrhizal fungi and that the absence of mycorrhizal fungi retards the normal development of tree seedlings.

Reitveld (1974) reported on his research with substances produced by bunchgrasses which may retard the germination of ponderosa pine seedlings. Other investigators have suggested that the survival of mycorrhizal fungi in the absence of symbionts is precluded in grassland soils by toxic or antibiotic substances emitted by roots of grassland plants (Wilde, 1958).

The deterioration of direct tree seedlings may be caused by a lack of mycorrhizal fungi. It is, however, possible to grow mycotrophs in the absence of mycorrhizal fungi with the application of large amounts of nutrients (Harley, 1969). With artificial inoculation, the application of abnormal amounts of nutrients is neither necessary nor economically practical.

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